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OTHER OPTIONS
e^-e^-, $e^-\gamma$ and $\gamma\gamma$ Physics at a Linear Collider

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ABSTRACT

The technical problems and the physics programme are reviewed for each of the options. Running with e^-e^- for part of the time is surely feasible and may have some real advantages. Making a $\gamma\gamma$ or an $e\gamma$ collider will not be so simple, but there are important physics benefits. If a Higgs boson is seen with mass less than 350 GeV/c^2 then the $\gamma\gamma$ machine must eventually be built.

1. Introduction

A better title for this talk would be "The Rest of the Programme at a Linear Collider". All three non e^+e^- options have important contributions to make to the study of the standard model and of possible physics beyond the standard model; and at least one major urgent job may need to be done in the $\gamma\gamma$ mode of operation. After a brief outline of the accelerator questions involved in each option the main physics goals are reviewed. There is only time to mention an arbitrary personal selection of the ideas presented in recent workshops - here at LCWS 95, at the European workshop in DESY two weeks ago[1], at Gran Sasso in May, at Photon '95 in April[2], at LC95 in March and at the dedicated LBL $\gamma\gamma$ workshop in April 1994[3]. I conclude with a judgement on how each of the options might be incorporated into the Linear Collider programme.

2. The e^-e^- Programme

2.1 e^-e^- Collider Questions

Making a second electron beam is clearly a solved problem, merely a matter of providing a second electron source on the positron side of the e^+e^- collider. It is important for the physics that both e^- beams should be polarisable up to ~90% in either sense. This will be particularly useful if it turns out that the e^+ beam cannot be polarised. The luminosity in the e^-e^- mode will be significantly smaller than the e^+e^- luminosity because of the anti-pinch effect. The reduction will vary with the beam parameters. For Tesla[4] it is about 1/5. The extra cost of providing the e^-e^- mode is tiny compared with the cost of the whole project. When and whether the linear collider runs in e^-e^- or in e^+e^- mode will be a physics question, not a question of cost or technology.

2.2 Advantages of e^-e^- Running.

Although many of the channels studied in e^-e^- have equivalents in e^+e^-, some of the dominant standard model processes from e^+e^- are absent, $Z^o\gamma$, W^+W^- and $q\bar{q}$ for instance. This cuts down background, especially in the hadronic channels which might mask exotic new signals. Assuming that both beams can be 90% polarised, it will be

Invited talk given at LCWS '95, the workshop on physics at a high energy electron-positron linear collider, Morioka-Appi, Japan, 8-12 September 1995.

possible to compare event rates in $e_R e_R$, $e_L e_L$ and $e_R e_L$. In particular, $e_R e_R$ scattering will damp down couplings to W^{+-}, further reducing backgrounds to non-standard channels. With reduced Z and W production, final states with high-p_T $\mu^-\mu^-$ or $\mu^- e^-$ will tag new physics. Also, at $\sqrt{s}$=1 or 1.5 TeV, $V_L^- V_L^-$ scattering can be studied with I-spin = 2, complementing what can be seen in e^+e^-

2.3 New Physics in e^-e^-.

Cuypers, Minkowsky and Heusch [see their contributions to these proceedings, and the proceedings to be published of their recent Santa Cruz workshop] presented a range of studies for which e^-e^- will be particularly useful. Selectron production (Figure 1) will have cross sections approaching 1 pb for some choices of the SUSY parameters. The signal is final-state e^-e^- with large missing energy, and Cuypers claims that the backgrounds from Møller scattering and from W or Z bremsstrahlung can easily be cut out.

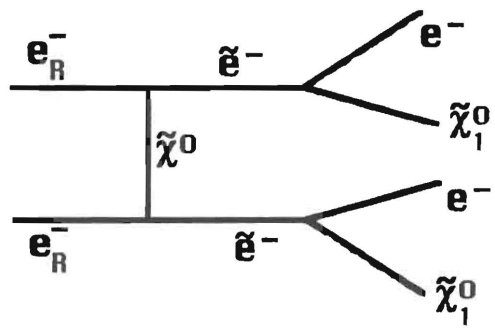


Figure 1. Selectron production and decay.

Møller scattering itself could have non-standard contributions which would give noticeable signals. A run of 20 pb^{-1} at a 500 GeV e^-e^- machine would be sensitive to Z' exchange in the t-channel with 90% significance for couplings to the Z' of 8% of the standard Z^0 coupling and Z' masses up to very large values, well beyond 2 TeV. For the same integrated luminosity e^+e^- would see a signal of the same significance only if the coupling is as big as 15% of standard - but remember that e^-e^- instantaneous luminosities will always be considerably smaller than e^+e^-. There will also be sensitivity in Møller scattering to the $e^-e^- \rightarrow e^-e^-$ contact potential.

2.4 Standard Model Physics in e^-e^-

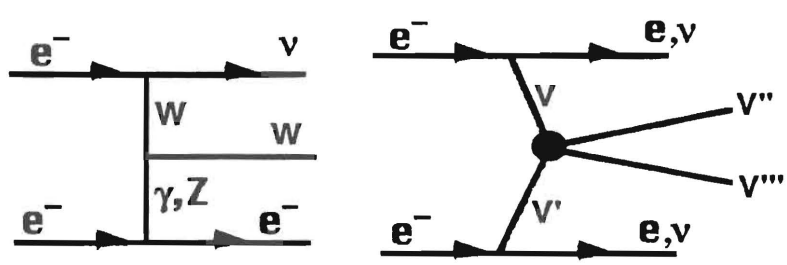


Figure 2. Trilinear and quadrilinear couplings in e^-e^- scattering. The vector bosons V,V' etc. can be any allowed combination of γ,*W* and *Z*.

The trilinear and quadrilinear gauge boson couplings (Figure 2) can be studied in e^-e^- with a great variety of channels ($W^-e^-\nu$, $W^+W^-e^-e^-$, ZZe^-e^-, $W^-W^-\nu\nu$, $W^-Ze^-\nu$). Yuan (these proceedings) has shown the beginnings of a classification of all the possible terms in the Electroweak Lagrangian, with their sensitivity to analyses in different possible e^+e^- and pp final states. This approach needs to be expanded to include the contributions from e^-e^-, $\gamma\gamma$ and $e^-\gamma$. Boudjema's discussion (these proceedings) shows how a particular pair of candidate anomalous terms from the general Lagrangian - L_{9L} and L_{9R} - can be constrained in different ways by analyses of different channels. A complete study may need all accessible final states from all four linear collider options as well as data from the LHC.

3. How $\gamma\gamma$ and $e\gamma$ colliders work.

3.1 Fundamentals

Backscattered laser beams were first used at SLAC[5] to provide a useful flux of high energy photons for bubble chamber experiments. The Novosibirsk group[6] then suggested that it would be possible to backscatter laser photons from both beams of a high energy e^+e^- or e^-e^- collider. Telnov[7] has given a clear survey of the relevant principles, part of which is summarised here. A dimensionless variable is defined;

$$x = \left(\frac{4E_0\omega_0}{m_e^2}\right)\cos^2(\alpha_0/2) \approx 15.3\left(\frac{E_0}{TeV}\right)\left(\frac{\omega_0}{eV}\right),$$

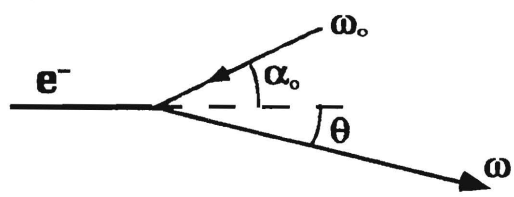


Figure 3. Kinematics of Compton Scattering of a laser photon with energy ω_0 making a high energy gamma with energy ω.

where α_0 is the angle between the electron beam and the laser beam, figure 3, with $\cos^2(\alpha_0/2) \approx 1$ for the most probable regime of close to head-on collisions. ω_0 is the energy of a laser photon. Two simple QED processes will by-pass the production of high energy backscattered photons if ω_0 is allowed to get too big. Denoting the laser photon as γ_0 and the high energy scattered photon as γ, if the invariant mass of the $e\gamma_0$ system is too high the process $e + \gamma_0 \rightarrow e + e^+ + e^-$ will occur. This is avoided by keeping $x < 8$. If the invariant mass of the $\gamma\gamma_0$ system is too high we get $\gamma_0 + \gamma \rightarrow e^+ + e^-$, avoided by keeping $x < 4.8$. The latter limit is often assumed to set the wavelength of the laser to be used with a particular beam energy E_0 [$\lambda_{x=4.8} = 4.2E_0(TeV)\mu m$], giving the relation shown in figure 4 between the two scattering angles. Choosing $x = 4.8$ reduces the maximum energy of the backscattered photons to about 80% of E_0. For a 500 GeV (C. of M.) linear collider the incident laser light should have wavelength $\lambda_{x=4.8} \cong 1\mu m$, which could be produced by a number of

current laser techniques[3]. For a 5 x 5 GeV low energy collider[8] $\lambda_{x=4.8} \cong 0.02\mu m$, which may be more difficult.

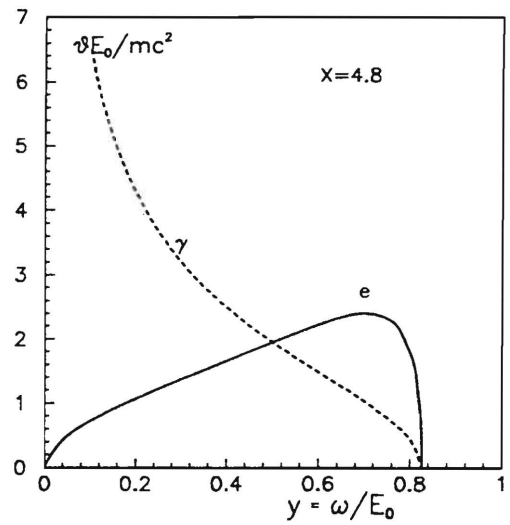


Figure 4. Electron and photon scattering angles versus photon energy[7] for x=4.8.

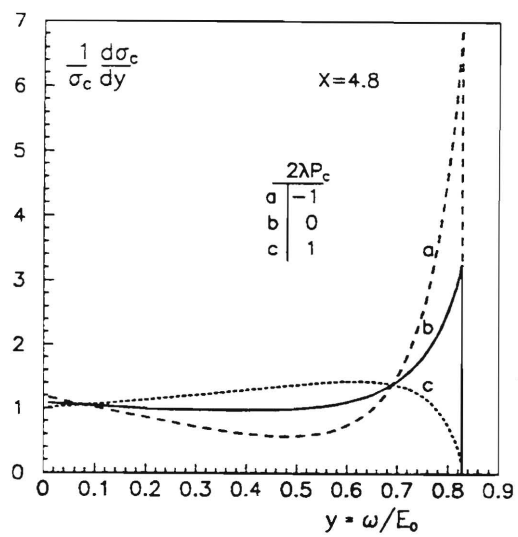


Figure 5. Energy spectra of scattered photons for different products of electron and laser circular polarisation[7].

If the laser beams and the electron beams can all be polarised there is good control over the spectrum of the primary backscattered photons. Figure 5 shows the energy of primary photons produced in scatters between full energy electrons and laser photons. But the remaining lower energy electrons can scatter from the laser pulse again, producing low energy secondary backscattered photons. For a "thick" laser pulse, offering more than one interaction length to the incident electrons, figure 6 shows how the number of lower energy secondary photons can far exceed the number of primaries. Lower energy primary photons, and the secondary photons, are at larger angles to the beam direction than the high energy primaries so it is possible to reduce

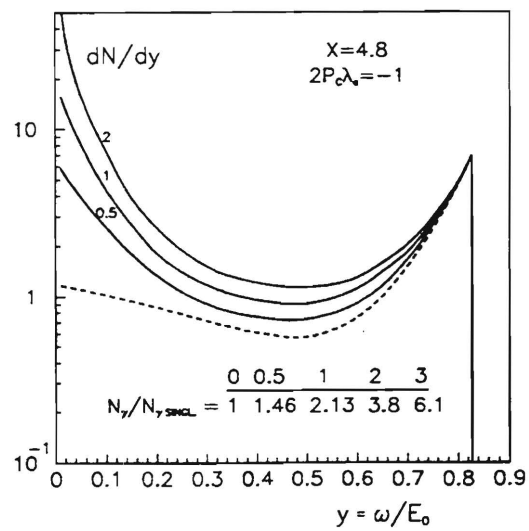


Figure 6. Photon spectra, normalised to peak, for different numbers of interaction lengths in a laser target. Solid (dashed) curves include (exclude) secondary scatters[7].

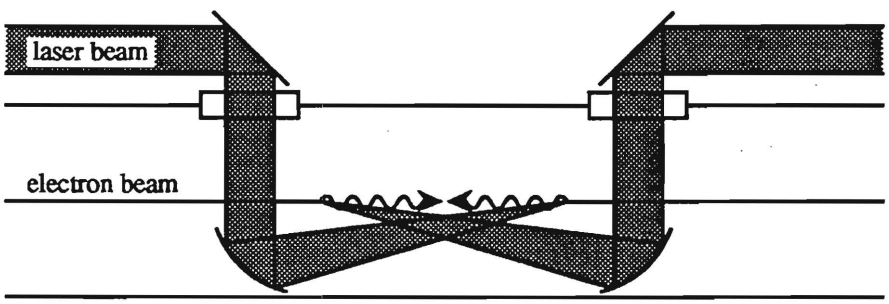


Figure 7 schematic design for a photon linear collider[9].

the contribution of low energy photons to the collision rate by intersecting the laser beams with the incident electrons at a finite distance from the collision point; see figure 7. Figure 8 shows $\gamma\gamma$ luminosities as a function of $W_{\gamma\gamma} \equiv \sqrt{s_{\gamma\gamma}}$ for collisions of primary photons with either no spacing between the conversion and the interaction points, "ρ=0", or with a finite spacing, "ρ=1". Here $\rho = b/\gamma a_c$, with b the distance from the conversion points to the interaction point, a_c the r.m.s radius of the colliding electron beams at the i.p. and $\gamma = E_0/m_e$. For 250 GeV beams with a_c=20 nm (say), ρ=1 corresponds to b = 10 mm. (The simplifying assumption of round beam spots has been made. This may not be feasible.) If both laser beams have opposite helicity to their electron beams, as in the lower dashed curve in figure 8, it would be possible to reduce the effective width of the peak to $\Delta W_{\gamma\gamma}/W_{\gamma\gamma} \cong 10\%$. This is often called the monochromatic $\gamma\gamma$ collider. It will be particularly attractive for dedicated Higgs studies, if any neutral Higgs bosons are found with masses of less than about 350 GeV/c^2 (see

section 4 below). Since both high energy beams need to be highly polarised for the monochromatic collider it is likely to be operated in e^-e^- mode rather than e^+e^-.

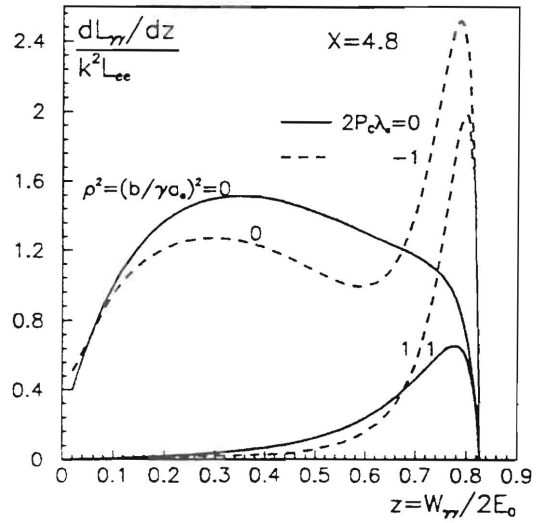


Figure 8 Spectral luminosity of $\gamma\gamma$ collisions[7]. The upper pair of curves is for ρ=0, i.e. no spacing between conversion and collision points. The lower pair is for ρ=1.

In a recent presentation of the monochromatic scenario, using the beam spot sizes of current e^+e^- collider designs, Telnov[10] estimated that the $\gamma\gamma$ luminosity in the peak would be 1/10 of the geometric lepton-lepton luminosity (i.e. neglecting disruption). Schulte[11] has checked Telnov's analytic calculations with a Monte Carlo programme set up for the TESLA collider, confirming the main features of Telnov's results. The optimised laser pulses would present a thickness of one interaction length to the incoming electron beam at the conversion point. Telnov pointed out that e^+e^- beam spots at the intersection point have a very large ratio between the horizontal and vertical r.m.s. in order to achieve good luminosity with low disruption and beamsstrahlung. The damping rings, linacs and final focus are all optimised for e^+e^- operation. Discussion with machine designers at LC'95 and at the TESLA workshop in Gran Sasso confirmed that it may be possible to reduce the horizontal to vertical ratio by building special $\gamma\gamma$ intersection-region optics, bringing the effective luminosity up to about 1/5 of geometric. If the highest possible $\gamma\gamma$ luminosity were required then it would be necessary to redesign the damping rings and the linac itself to produce the smallest possible beamspot cross-section (though a truly round spot will never be optimal, for optical reasons). In this case the $\gamma\gamma$ luminosity might be as much as 1/2 of geometric.

With a different combination of beam and laser helicities, and a reduced value of ρ, a $\gamma\gamma$ collider could be operated in an alternative wide-band mode, e.g. the upper solid curve in figure 8. This would be useful in searching for narrow resonances with large cross sections - though it is unlikely that a Higgs boson would be found first in this way. Either LEP2, the LHC or the parent e^+e^- linear collider are likely to have found the Higgs already if it is in the available mass range up to 350 GeV/c^2 where a $\gamma\gamma$ collider could resolve it from background.

The circular polarisation of the primary scattered photons can be high over most of the peak momentum range of the "monochromatic" beam[7?] but a high degree of transfer of linear polarisation from the laser to the backscattered beam can only be achieved[12] if the laser photon energy is significantly reduced from the value corresponding to $x = 4.8$. (See discussion in 4.2 below for how this might be used in determining the parity of Higgs bosons). The reduction in the incident photon energy would, of course, give a peak $\gamma\gamma$ collision energy of significantly less than 80% of full collider energy.

As a lower cost demonstrator for the principles of $\gamma\gamma$ colliders, a low energy $\gamma\gamma$ collider [8?,13] could use the wide-band mode to study resonances in the mass range from 1 to 4 GeV (say), including measurements of the "stickiness" of glueball candidates and precise determination of $\gamma\gamma$ partial widths for η_c and the χ_cs. Yurkov and colleagues[14] have even suggested using the SLC with very intense laser pulses, presenting much more than one interaction length to the incoming electrons, to generate very large numbers of low energy gammas (c.f. uppermost curve in figure 6). This is the only scenario known to me in which it might just be possible to produce enough η_b particles for worthwhile study[15].

3.2 Intersection Region Problems.

Some specially awkward questions arise:

a) How do we get the laser beams to focal spots only a few wavelengths wide at the conversion points, which are a few millimetres from the interaction point, buried deep inside a large detector?

b) Do we need very localised high magnetic fields to deflect the electrons after the conversion point so that they do not collide at the intersection point?

Both of these questions were tackled at the LBL worskhop [15 16 17]. A further important question related to b) was posed very clearly at Gran Sasso:

c) Must a $\gamma\gamma$ collider have a large beam-crossing angle?

The following discussion reviews what was said about these questions by participants in the workshops but does not pretend to give the final answers.

Question a) The laser beams will need focusing elements close to the conversion points, probably inside the machine vacuum. These could be mirrors, but to achieve waists of a few microns they will need to be inside the last low beta quadrupole of

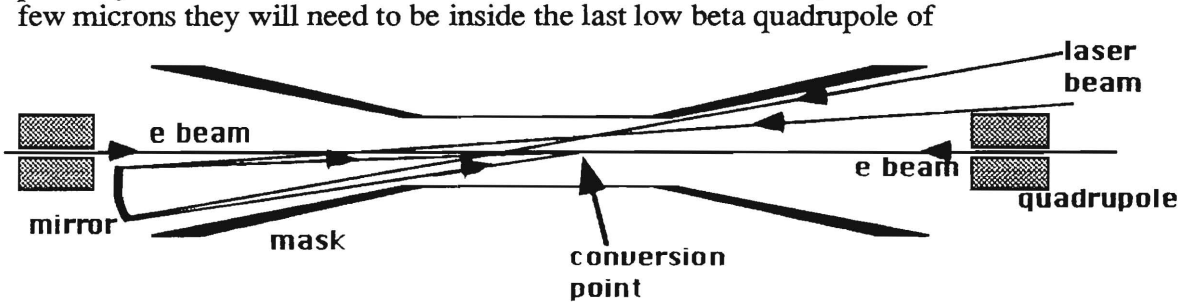


Figure 9. Sketch of a layout for laser optics in the intersection region. Two such systems would be needed for $\gamma\gamma$ collisions. The tungsten mask is to stop soft backscattered radiation from the quadrupole region from reaching the trackers. It may have to cover a wider cone for $\gamma\gamma$ than for e^+e^-.

the linac and to be some centimetres in diameter. Figure 9 is a sketch of a possible layout. To maintain the required optical performance the mirrors must be kept out of the zones of intense particle radiation associated with the outgoing disrupted (or deflected)

electron beams (see discussion of question c). The incoming laser beams will have to be brought past the low beta quadrupoles, inside the conical tungsten masks which stop soft scattered radiation which hits the front of the quadrupoles from splashing back into the central tracking detectors. To make room for the laser beams the mask for $\gamma\gamma$ experiments may need to have a larger half-angle than for e^+e^-, giving a loss of physics acceptance in the forward regions. Experimenters would be very unhappy for the laser beams to be brought in a right angles to the linac, through the detectors. Such a geometry would interfere seriously with the hermetic coverage which is needed for much of the physics to be done at a $\gamma\gamma$ collider. For linacs with a separation of only a few nanoseconds between bunches it has been suggested that the laser beams could be multiply reflected through the conversion points. This would require mirrors with superb reflectivity to survive for long periods in the very hostile environment of the vacuum chamber[16].

Question b) If the remains of the converted electron beams are allowed to continue undeflected to the intersection point there are at least two unwanted effects:

i) the electron beams will disrupt one-another and produce a very large range of angles in the outgoing beam;

ii) there will be a significant rate of $e\gamma$ collisions providing background to the $\gamma\gamma$ channels (e^-e^- background in the $e\gamma$ mode may not be so serious).

Telnov has suggested[7] that small superconducting sweeping magnets could be mounted close to the intersection point to provide a few Tesla-millimetres of bending between conversion and interaction, sufficient to make the electrons miss the interaction point by a few hundred nanometers. No one has produced a satisfactory design for such a magnet[15 17]. It should present a negligible thickness of material to tracks going out towards a vertex detector (especially important for Higgs decaying to beauty pairs). It must be mechanically strong enough to withstand the magnetic forces. It must give zero field at and before the conversion points to avoid deflecting the photon spots. Balakin[18] showed at LBL that, for the ultra high current beams of the VLEPP collider, the coherent fields of the two e^- spots would be strong enough to deflect one another and avoid direct collisions, but this would not happen for any of the other linear colliders at present under discussion. Norem[19] suggested that a plasma lens, of the kind discussed also by Chen and colleagues for $e\gamma$ physics[20], could be formed by puffing gas jets between the conversion and interaction points. The plasma would overfocus the electrons before the interaction point so that they would have diverged before they reached it. Experimenters worry about how the gas from the jets can possibly be pumped away without serious obstruction of the interaction region.

Question c) The reader will have noted that in every scenario discussed above in connection with question b) the spent electrons are - in one way or another - bent aside or disrupted. For example, in Telnov's optimised monochromatic collider the energies of these electrons would be double-peaked, at beam energy (for the 35% unconverted), and at about 20% of beam energy. To sweep away the full energy electrons it will be necessary to sweep the converted electrons a factor of 5 further away. But there will also be a large number of electrons which have made multiple collisions and these will be swept to even larger angles. This outgoing shower of electrons will carry a considerable amount of energy per burst. Not only must they not be allowed to hit the laser mirrors, they must also be kept away from any superconducting or permanent magnets - the two most likely technologies for low beta quadrupoles. The only way to do this will be to have a significant beam-crossing angle in the $\gamma\gamma$ and $e\gamma$ collider modes, which would be

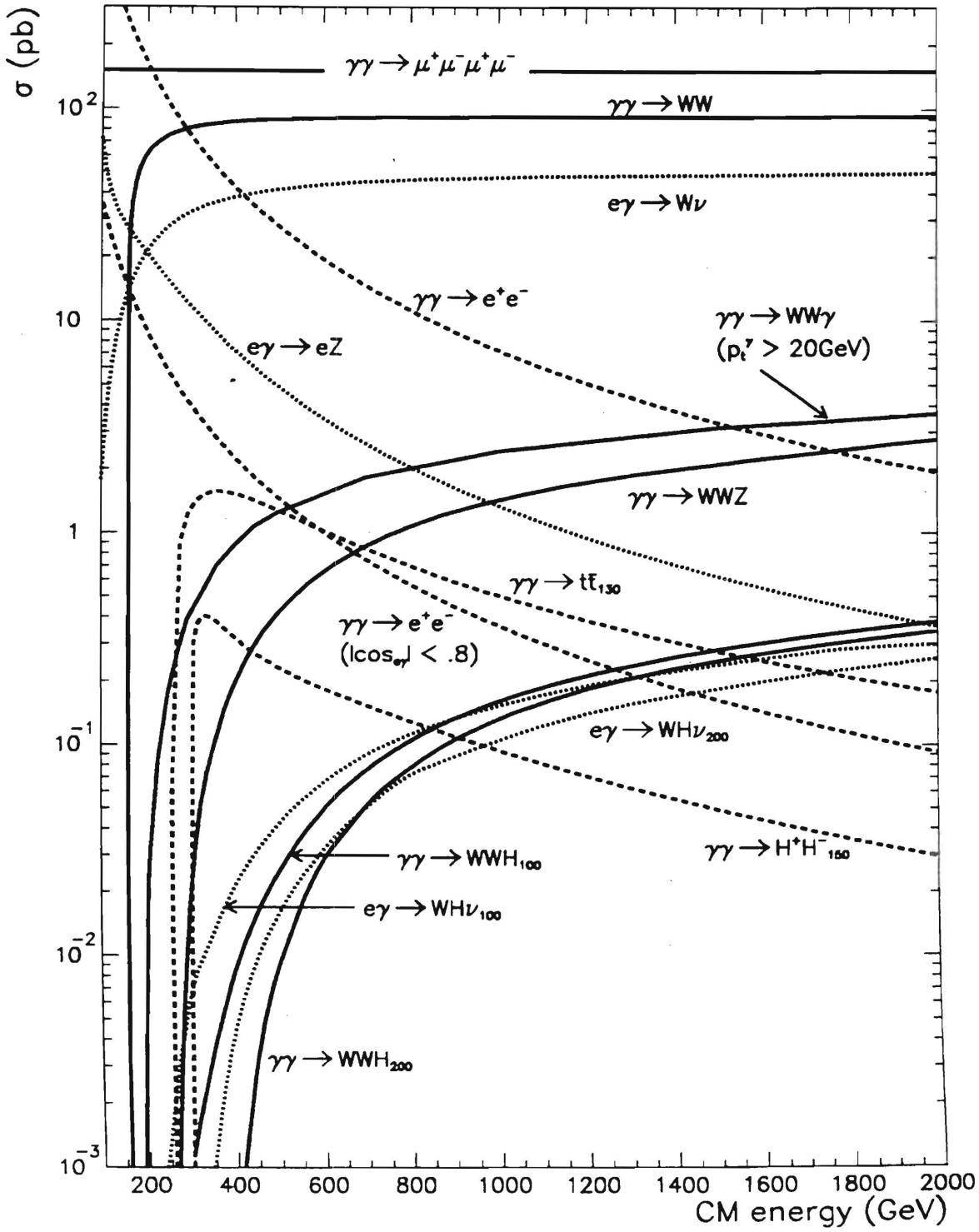


Figure 9a (preprint version only). Comparison of cross sections for some final states between e^+e^-, $\gamma\gamma$ and $e\gamma$ [31].

incompatible with current final-focus plans for the e^+e^- mode at some of the planned colliders - at TESLA, for instance, as reported at Gran Sasso.

None of these questions is a real show-stopper. It may be necessary to live with the backgrounds due to unswept electrons; there will still be clear physics signals. It may be necessary to have a special $\gamma\gamma$ intersection region with a finite crossing angle and its own optimised detector. And it may be necessary to use a free electron laser[21] to match the linac pulse structure so that multiple reflections are not needed. The conclusion at Gran Sasso was that solutions will be found - if the $\gamma\gamma$ physics programme is good enough.

4. Physics at a $\gamma\gamma$ collider.

4.1. Cross Sections and Angular Distributions.

The cross-sections for many final states in $\gamma\gamma$ collisions, $\gamma\gamma \rightarrow W^+W^-$ and $\gamma\gamma \rightarrow W^+W^-Z$ for instance are much larger than the equivalent cross-sections in e^+e^- (see figures in Boudjema's review, or figure 9a). Figure 10 shows how a significant part of this extra cross-section may be lost because the angular distributions of many of these states are strongly peaked in the forward-backward direction. We can expect to loose even more of the forward tracks in a $\gamma\gamma$ detector because the shielding masks are likely to cut off a larger cone around the beam direction than in e^+e^- (see section 3, above).

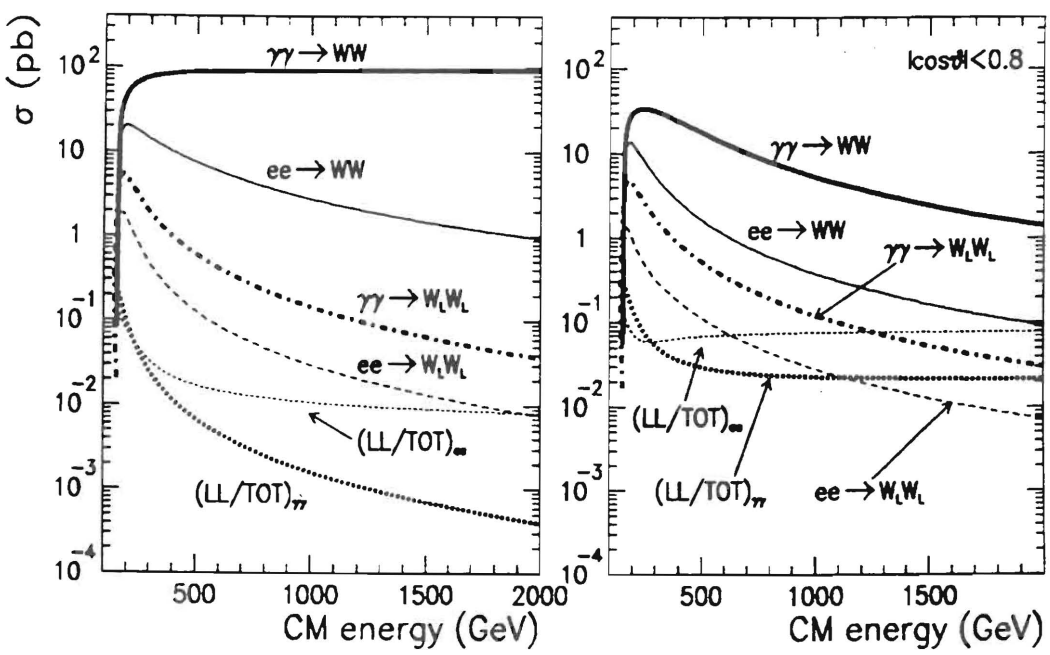


Figure 10. Comparison of e^+e^- and $\gamma\gamma$ cross sections for W^+W^- production. Realistic angular cuts remove a large part of the cross sections in both channels[31].

4.2 Higgs Physics at a $\gamma\gamma$ collider.

The "star" channel is $\gamma\gamma \rightarrow H^0$, if the Higgs boson mass is below 350 GeV/c^2. Neutral Higgs bosons will be seen as clear resonant enhancements in $\gamma\gamma \rightarrow b\bar{b}$ up to about 150 GeV, or in $\gamma\gamma \rightarrow Z^0Z^0$ up to 350 GeV[22 23]. Study of the $b\bar{b}$ channel will require excellent flavour-tagging - especially if M_H is close to M_Z, where the 85% beauty branching ratio of the Higgs will enhance the signal compared to the background of $Z^0 \rightarrow b\bar{b}$ which has only a 15% branching ratio. The $\gamma\gamma \rightarrow H^0 \rightarrow W^+W^-$ signal will be swamped by copious $\gamma\gamma \rightarrow W_T^+W_T^-$ continuum signal, but Jikia has shown[24] that the lower $\gamma\gamma \rightarrow Z_T^0Z_T^0$ continuum rate will not swamp the resonant $\gamma\gamma \rightarrow H^0 \rightarrow Z_L^0Z_L^0$ channel for $M_H \leq 350 Gev/c^2$ (Figure 11).

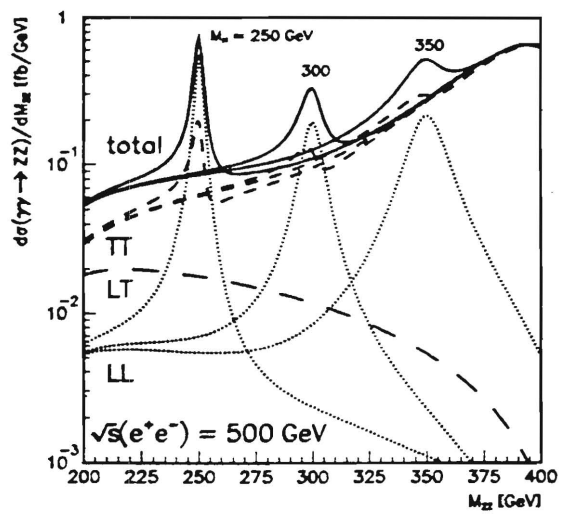


Figure 11. Invariant ZZ mass distributions in resonant (LL only) and continuum ZZ production for three possible Higgs boson masses[24].

If it exists, a standard model H^0 below 350 GeV, or the lightest Supersymmetric h^0 will almost surely have been found already before running begins in the $\gamma\gamma$ mode, either at LEP2, at LHC or at the e^+e^- Linear Collider. It will then be possible to set the e^-e^- linac energy to $2E_b \approx M_H/0.75$ and operate in the narrow band mode (see discussion above), choosing the circular polarisations of the beams and the lasers to give $J_Z = 0$ collisions in order to suppress the $\gamma\gamma \rightarrow b\bar{b}$ background which is only produced in $J_Z = 2$ at lowest order. Since Borden's discussion at Waikoloa[22] it has been pointed out[25] that photon-gluon fusion, the "singly resolved" process (Figure 12), will give a continuum $b\bar{b}$ and $c\bar{c}$ contribution in $J_Z = 0$ also. This has been discussed both at[26] and after[27] the LBL workshop and it was concluded that the invariant mass spectrum of the $b\bar{b}$ and $c\bar{c}$ pairs from the fusion process will have only a small tail under the peak at M_H. Watanabe

(these proceedings) has also looked at the question of identifying the $H^0 \to b\bar{b}$ signal. He estimates that the partial width $\Gamma_{H\gamma\gamma}$ can be measured to 6% in 20 fb^{-1} of running for $M_H < 150$ GeV/c^2. In the region of the WW and ZZ thresholds the error on $\Gamma_{H\gamma\gamma}$ would be somewhat larger[22], but Borden estimated that it improves again to about 10% again above the ZZ threshold, from 200 to ~300 GeV/c^2.

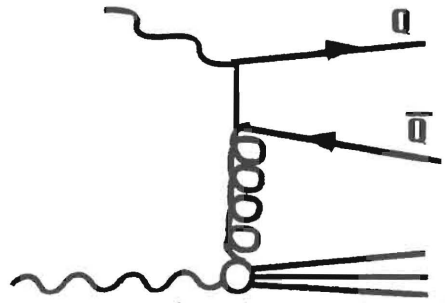
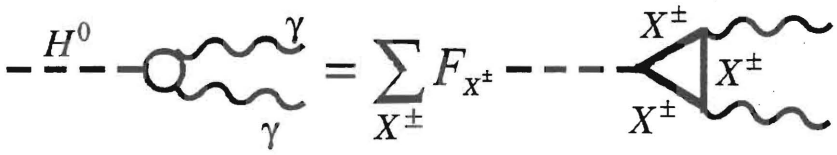


Figure 12. Heavy quark pair production in photon-gluon fusion; the singly resolved process: background to a possible Higgs signal..

The partial width $\Gamma_{H\gamma\gamma}$ is a very important parameter for at least two reasons:

a) Watanabe has reminded us here that the amplitude of the Higgs to $\gamma\gamma$ coupling has contributions from a sum of all available charged-particle loops:



where the coupling strengths $F_{X^\pm}$ reach their asymptotic values, corresponding to $M_{X^\pm} \to \infty$, for $M_{X^\pm} \geq M_W$. The size and the sign of an $F_{X^\pm}$ both depend upon the spin of the $X^\pm$ particle in the loop. The standard model value of the partial width $\Gamma_{H\gamma\gamma}$ is dominated by $t\bar{t}$ and WW loops, but it may be modified upwards or downwards by populations of charged fermions and bosons at scales which we cannot expect to reach with conceivable technologies. This is a unique window on physics up to very heavy scales.

b) If the LHC discovers a Higgs boson via $H \to \gamma\gamma$ decays, one of the major aims of both ATLAS and CMS, then it will be essential to measure $\Gamma_{H\gamma\gamma}$ in order to find out what kind of Higgs boson they have seen. The LHC rate will be proportional to the product $\Gamma_{H\gamma\gamma}.\Gamma_{Hgg}$. SUSY theories, for instance, give a wide and not necessarily correlated range of values for these two partial widths. Even if the LHC experiments observe the standard-model rate they cannot rule out many other models until $\Gamma_{H\gamma\gamma}$ is measured. Only the $\gamma\gamma$ collider offers a measurement to 10% accuracy.

Another important probe into the nature of a many-Higgs sector will be to measure the CP properties of every neutral Higgs boson detected[12 28]. This could, in principle, be done by counting the numbers of events in a Higgs signal as a function of the azimuthal angle ϕ between the linear polarisation vectors ε_1 and ε_2 of the colliding gammas. With ϕ=0 (modulo π) the scalar (and CP even) product $\varepsilon_1.\varepsilon_2$ is maximal, so CP even

eigenstates would be produced. With $\phi = \pi/2$, $(\varepsilon_1 \times \varepsilon_2 . k_\gamma)$ is maximal and CP odd eigenstates would be formed. CP violation could also be observed. It was mentioned in section 3 above that the transfer of linear polarisation between the laser photons and the colliding gammas is nowhere near as complete with the value of the Compton scattering variable set at x=4.8 as it is for substantially lower x values. For smaller x the ratio $y = \sqrt{s_{\gamma\gamma}}/2E_b$ gets smaller. Thus, even if LEP2 finds a Higgs boson with M_H<95 GeV/c^2 it will be necessary to use a much higher electron beam energy E_b to measure its CP properties. According to Gunion and Kelly [29] the 250x250 GeV Linear Collider will be able, in principle, to do this measurement at close to the optimum polarisation conditions for all Higgs bosons found with M_H<150 GeV^2. And, if SUSY is kind and we find three Higgs bosons - two with CP+ and one CP-, they claim that an e^-e^- collider with 750x750 GeV could do the optimised experiment for all three of them, if their masses are less than 450 GeV/c^2. I should warn that I have not yet seen an experimental study of how this physics could be done, even at the generator level of Borden's work on $\Gamma_{H\gamma\gamma}$. There could be problems that have not been identified.

For M_H>350 GeV/c^2 the $\gamma\gamma$ collider could do Higgs physics in such channels as $\gamma\gamma \to t\bar{t}H$ or $\gamma\gamma \to WWH$ [30 31]. In the absence of a light Higgs boson the $\gamma\gamma \to WWZZ$ and $\gamma\gamma \to WWWW$ channels would be sensitive to strong Electroweak symmetry breaking. Their cross sections are higher than the e^+e^- equivalents, but again the lower energy and intrinsic luminosity of the $\gamma\gamma$ mode is likely to cancel out most of this advantage - except that $\gamma\gamma$, like e^-e^-, can access I-spin = 2 WW states which cannot be produced in e^+e^-.

4.3 Non-Higgs Physics at a $\gamma\gamma$ Collider.

Despite the probable loss of useful events due to angular cuts, shown in Figure 10 above, cross sections for many processes are higher at the gg collider than for e^+e^-. For example:

$$\sigma_{\gamma\gamma\to WW}(400GeV) \approx 20.\sigma_{e^+e^-\to WW}(500GeV);$$

so if the luminosity of the $\gamma\gamma$ collider can be brought to within a factor of two of the e^+e^- luminosity the $\gamma\gamma$ machine would be a copious W factory - for final state W-decay studies as well as for production processes. Jikia has reported here that the radiative corrections to $\gamma\gamma \to W^+W^-$ are not overwhelmingly large and are well understood. Boudjema and collaborators[31] have shown how a simple study of $\gamma\gamma \to W^+W^-$ would provide extra constraints on the anomalous triple gauge boson couplings, as mentioned in *2.4* above. A more sophisticated study, using angular distributions in the W decays along the lines reported here by Barklow, would be even more sensitive to the couplings.

Threshold studies in the $\gamma\gamma \to t\bar{t}$ channel would, in principle[32], be as interesting as in $e^+e^- \to t\bar{t}$. But the 10% energy spread on $\sqrt{s_{\gamma\gamma}}$, compared with only 0.2% on $\sqrt{s_{e^+e^-}}$ at an optimised linac, means that the $J^{PC}=0^{-+}$ threshold excitation in $\gamma\gamma$ can never compete with the 1^{--} excitation in e^+e^- for constraining m_t, Γ_t, α_S etc.[33 34]. Choi has shown at this workshop that with linearly polarised photons $\gamma\gamma \to t\bar{t}$ can be used to look for CP violation.

Hadron jet production in $\gamma\gamma$ collisions[35 36] will be sensitive to the gluon distribution inside the photon - complementing the quark distributions which will be measured best in $e^-\gamma$ collisions, see 6.1 below.

5. Physics at an $e^-\gamma$ Collider.

5.1 The Photon Structure Function F_2^γ

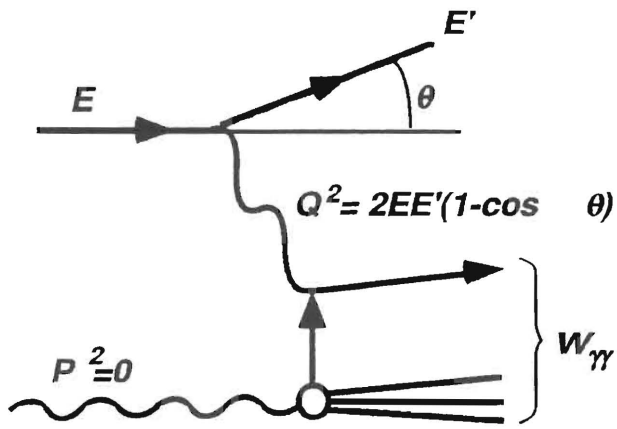


Figure 12. Deep inelastic scattering from a real photon.

We would like to do deep inelastic scattering on real photons (Figure 12). Until the $e\gamma$ collider is available, measurements of $F_2^\gamma(x,Q^2)$ will continue to rely on using one of the leptons at an e^+e^- collider to probe the rather soft Weiszäcker-Williams spectrum of virtual photons radiated by the other lepton. Experiments of this kind at PEP, PETRA, TRISTAN and LEP have established[37 2] two important features of the structure function:

a) For Q^2 of the probe greater than about 5 GeV^2 and Bjorken $x > 0.1$ the size and x-dependence of $F_2^\gamma(x,Q^2)$ is consistent with the predictions of well established QCD models, either in leading or in higher order.

b) For $Q^2 \leq 3GeV^2$, in the accessible range of x, the size and x-dependence of $F_2^\gamma(x,Q^2)$ is consistent with a Vector Meson Dominance picture in which the target photon behaves like a pre-existent hadron with quark content similar to that deduced for the pion from Drell-Yan processes.

It cannot yet be claimed that either the QCD-like behaviour a) or the VMD-like hadronic behaviour b) has been proved to be due to the model which describes it. For a) it will be necessary to go to much higher values of Q^2 to demonstrate the evolution of $F_2^\gamma(x,Q^2)$ with $\ln Q^2$. For b), the observation at HERA that $F_2^{proton}(x,Q^2)$ rises for $x \leq 0.01$ has given support to a new set of QCD models such as GRV[38] which predict similar low x behaviour in $F_2^\gamma(x,Q^2)$. There is debate about whether the rise seen at HERA in $F_2^{proton}(x,Q^2)$ at low x is a manifestation of the BFKL effect[39] or whether it can be explained by Altarelli-Parisi evolution. The LEP1 experiments[40 41] are just reaching the edge of the interesting low x region. The structure function working group[42] in the 1995

LEP2 physics study agrees with the prediction[43] that the extended kinematic range of LEP2, with the expected higher integrated luminosity, should enable us to see a low x rise if it starts at the same x values as for the proton. But already at LEP[44] there are experimental problems in measuring the lowest values of $x = Q^2/(Q^2 + W_{\gamma\gamma}^2)$ because, for virtual Weiszäcker-Williams target photons, the $\gamma\gamma$ invariant mass $W_{\gamma\gamma}$ can only be estimated from the observed hadronic system - which is less and less accessible at smaller x because the target photon fragmentation becomes more and more peripheral, giving some forward hadrons which are hard to measure. At the linear collider these hadrons will literally go down the beampipe, rather than into the forward luminosity calorimeters as they do at LEP. (This undermines some of the $\gamma\gamma$ programme we advertised at Waikoloa[45]).

An $e\gamma$ collider will transform this situation by providing a high flux of real target photons at close to the full electron linac energy. The reach in Q^2 and the event statistics will be much greater than at any other machine and, if we use the monochromatic mode for production of the photons (section 3 above), the invariant mass $W_{\gamma\gamma}$ can be calculated without needing to use reconstructed hadrons - giving a much more reliable value of x. To exploit this opportunity we must provide a tagging detector which can measure the scattered probe electron to within about 40 milliradians of the beam direction. It will sit well inside the tungsten mask (Figure 9) so it will need to be capable of resolving electrons at and above half beam energy in the presence of intense soft electromagnetic background radiation (Fuji-san, these proceedings, wants a similar detector as a veto, and it would also be useful as a coarse luminosity monitor). At the European workshop meeting[1], August 1995, Vogt showed preliminary calculations of event rates for $e\gamma$ at 500 GeV linear collider. Even with modest luminosity there will be good statistics up to $Q^2 \approx 10^4 GeV^2$. It will be important to tag down to 40 mr in order to overlap with the lower Q^2 data from LEP2, and to give access to reasonable low x (~2.10^{-3} at $Q^2 \approx 100 GeV^2$. By fitting $F_2^\gamma(x,Q^2)$ from a combined LEP2 and $e\gamma$ collider dataset, Vogt anticipates that a new precise measurement of α_S will be possible, without much model dependence. (This will also provide a definitive test of the QCD evolution in region a) of the structure function, discussed above.)

To investigate the very low x behaviour of $F_2^\gamma(x,Q^2)$ it would be necessary to tag electrons down to much smaller angles. This might be done with a specialised calorimeter some meters downstream of the intersection point, where there could be room for a bending magnet to separate the wanted electrons from electromagnetic background and disruption products. Tagging down to 10 mr would give access to $x \approx 10^{-4}$ for $Q^2 \approx 10 GeV^2$.

5.2 Gauge Boson Couplings in $e\gamma$..

As mentioned in *2.4* above, $e\gamma \rightarrow W\nu$, figure 13b), will be part of the complete set of measurements to determine all possible triple gauge boson couplings. Its cross section is large (see reviews of Boudjema and collaborators, these proceedings and[31]). There have been suggestions that this might even be possible at the SLC[20].

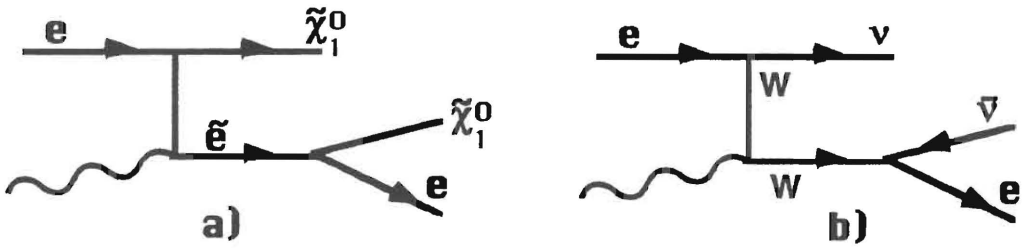


Figure 13. a) Selectron production and decay in eγ. b) The Wν process which could give background to a), if the selectron mass is close to the W mass.

5.3 New Physics in eγ.

Selectrons accompanied by the unseen lightest neutralinos, figure 13a), will have a characteristic signal[46] of a single large-angle electron. The selectron mass would be measured from the Jacobian peak in the transverse momentum distribution (if it is not too close to the W boson mass). The possibility of seeing leptoquarks in eγ collisions has been discussed by Cuypers (these proceedings) and by Belanger *et al*[47].

6. Conclusions

1. For me there is one "star" reason for building a γγ collider, to measure $\Gamma_{H\gamma\gamma}$ - assuming the Higgs boson has already been found at LEP2, at LHC or at the parent e^+e^- collider. As explained in section 4.2 above, if we have seen $M_H \leq 350 GeV/c^2$ before the e^+e^- linac is completed, then γγ must be built-in from the start.

2. e^-e^- must be available from the start, with polarisation of both beams. When it runs will depend upon the physics:-

Is SUSY alive and well?
Are anomalous couplings suspected?
Do we need a Majorana neutrino?

3. Whatever the physics outlook, both the γγ and the eγ options must be in the planned programme for a linear collider, but they may have to be staged for reasons of cost and because they will need extra technical development effort. Sessler said at LC'95 that it is important to decide, before the design of the e^+e^- linac is finalised, whether provision should be made for the special damping rings and final focus equipment required to achieve $L_{\gamma\gamma} \geq 0.5 L_{ee}$. This decision must be driven by physics arguments. Which channels need high luminosity, and can the experiments be done? No one has yet done realistic Monte Carlo studies of analyses of final states from γγ and eγ with anything near the thoroughness of the studies of Higgs, WW, SUSY etc. that have been done for the e^+e^- linear collider.

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