2.6 Experimentation

2.6.1 The Group

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2.6.2 Introduction

The purposes of this subgroup are to summarize:
(1) the important physics goals and their demands on the machine and detector,
(2) issues relating to the experimental programme,
(3) the effect of machine parameters on detector and experiment,
(4) generic detector possibilities,
(5) the areas of R&D which need close teamwork between machine and detector.

2.6.3 Physics

The physics discussion here and in the next subsection will be brief, in form of an executive summary. More details and references may be found in the Appendices.

The e^+e^- physics topics and examples of experiments with requirements on machine and detector are listed in Tables 1 and 2, which reflect the results of recent international workshops [1]-[16]. Three facets of the physics potential of the e^+e^- collider are:
(1) a programme of new physics, Table 1 – search for the Higgs boson and for physics beyond the standard model ($\mathcal{SM}$), for example supersymmetry ($\mathcal{SUSY}$);
(2) a rich programme of standard physics, Table 2 – measurements in hitherto poorly mapped regions of the $\mathcal{SM}$, such as top quark properties and trilinear gauge couplings, and measurements at in familiar regions such as QCD;
(3) a potential, the second topic of Table 1, for understanding the mechanism for the spontaneous breaking of electroweak symmetry even in the heavy, strongly-interacting Higgs scenario, which involves precision measurements of gauge boson production at the highest energy.

Further options are discussed below. Complementary theoretical predictions will be confronted in the e^-e^-, $\gamma\gamma$, and $e^-\gamma$ collider modes. Running on the Z^0 peak with polarized beams could measure $\sin^2\theta_W$ to greater accuracy than at LEP/SLC and provide the indirect M_{Higgs} determination to test the $\mathcal{SM}$ framework .

The main goal of next-generation colliders is to understand the origin of electroweak symmetry breaking ($\mathcal{ESB}$). The mechanism for $\mathcal{ESB}$ is most probably operating in the energy regime [11] of $\sqrt{s} \simeq \mathcal{O}(1$ TeV) or below, which will be accessed in complementary ways by the hadron colliders and the e^+e^- colliders.

2.6.4 Experimentation Aspects

Issues relating to the experimental programme are addressed here.

Experimentation phases

$\odot$ – At the international workshops the first-stage energy has been clearly demonstrated to be $\sqrt{s} \simeq 0.5$ TeV, which yields a healthy physics programme complementary to that of LHC.

If it would turn out to be advantagous to commission the machine at a lower energy, the following energies could be possible milestones, according to present knowledge:
–At $\sqrt{s} \simeq 0.3$ TeV with 1fb^{-1} of data, any measurement gap that might exist between LEP2 and LHC could be closed, a definitive test of the $\mathcal{SUSY}$-Higgs scenarios could be performed since in those models the lightest Higgs has $M_h \leq 150$ GeV/c^2 and

Table 1: Some e^+e^- new physics topics and the corresponding performance quality needed for machine and detector. Quality key: from"-" not important, to "$\star\star\star$" very important (LEP/SLC detectors $\sim \star\star$).

PHYSICS	MACHINE[a]				DETECTOR[b]						
	$\int \mathcal{L}dt$	$\sqrt{s}$	Narrow	Pol.	Herme-	Track-	Calor-	3-Dim.	Lepton	Vertex	pi/K
	fb^{-1}/y	TeV	$\mathcal{L}(\sqrt{s})$	beams	ticity	ing	imetry	Granul.	I.D.	Tag	I.D.
●HIGGS											
Light Higgs	1-10	.2									
Higgs spin-parity	20	to	$\star\star$[c]		$\star\star$	$\star\star\star$	$\star\star$	$\star\star$	$\star\star$	$\star\star\star$	$\star$
SM/Susy B.R.	100	$\sim$.5									
Interm. Higgs	200	$\sim$1									
●HEAVY, SRONGLY-INTERACTING HIGGS											
W_LW_L-scatt.	200	$\sim$1.5			$\star\star\star$	$\star\star\star$	$\star\star$	$\star\star\star$	$\star\star$	-	-
●SUSY											
Light $\tilde{t}$	10	.2									
$\tilde{\chi}_j^{\pm}, \tilde{\chi}_i^0, \tilde{\ell}$	10										
Susy spectroscopy	20	to		$\star$[d]	$\star\star\star$	$\star\star$	$\star\star$	$\star\star$[d]	$\star\star$	-	-
Susy parameters	100										
$\tilde{q}, \tilde{g}$	100	$\sim$1-2									
●EXTENDED GAUGE											
New particles	200	$\sim$2			$\star\star\star$	$\star\star\star$	$\star\star$	$\star\star\star$	$\star\star$	$\star\star$	
Overall from Tables 1,2			$\star\star\star$	$\star\star$[d]	$\star\star\star$	$\star\star\star$	$\star\star$	$\star\star\star$	$\star\star$	$\star\star\star$	$\star\star$

[a] Narrow c.m.s. energy spread arising from machine and beamstrahlung effects. $\star\star\star$ means the energy spread from the machine must be small ($\sigma \simeq \mathcal{O}(0.2\%)$); the luminosity spectrum must be well-measured (to the $\pm 0.1\%$ level); the last row of Table 2 describes the performance quality of the detector for measuring the luminosity spectrum.

[b] By "Tracking" and "Calorimetry" is meant the measuring accuracy for momentum and energy, respectively.

[c] If $M_{Higgs} \simeq M_{Z^0}$, upgrade to $\star\star\star$.

[d] If supersymmetry is discovered, upgrade to $\star\star\star$.

Table 2: Some e^+e^- physics topics related to known $\mathcal{SM}$ processes and the corresponding performance quality needed for machine and detector. Quality key: from"-" not important, to "$\star\star\star$" very important (LEP/SLC detectors $\sim \star\star$).

PHYSICS	MACHINE[a]				DETECTOR[b]						
	$\int \mathcal{L}dt$	$\sqrt{s}$	Narrow	Pol.	Herme-	Track-	Calor-	3-Dim.	Lepton	Vertex	pi/K
	fb^{-1}/y	TeV	$\mathcal{L}(\sqrt{s})$	beams	ticity	ing	imetry	Granul.	I.D.	Tag	I.D.
●ELECTROWEAK GAUGE BOSONS											
WWV-coupl.	10	.3									
Unfoldγ, Z-coupl.	50	to	$\star\star\star$	$\star\star$	$\star\star\star$	$\star\star\star$	$\star\star$	$\star\star$	$\star\star\star$	-	-
WWVV-coupl.	100	1									
●TOP QUARK											
Thr. scan	10	$\sim$.35	$\star\star\star$		$\star\star$	$\star\star$	$\star\star$	$\star\star$	$\star\star$	$\star\star\star$	$\star$
g-2,hel.anal.,V+A	50	.4									
Rare decays	50	to		$\star\star$	$\star\star\star$	$\star\star$	$\star\star$	$\star\star$	$\star\star$	$\star\star\star$	$\star\star$
Yukawa coupl.	100	1									
●QCD											
Hadronization	1	For									
Heavy flavors	10	all			$\star\star$	$\star\star$	$\star\star$	$\star$	$\star$	$\star\star$	$\star$
$\alpha_s(s)$	10	$\sqrt{s}$									
●(Virtual)$\gamma\gamma$											
Minijets	1										
$F_2^\gamma(x,Q^2)$	10		$\star$		$\star\star\star$[c]	$\star\star$	$\star\star$	$\star\star$	$\star\star$	$\star$	$\star$
Heavy flavors	10										
$\mathcal{L}(\sqrt{s})$ Det.[a]					$\star\star$	$\star\star\star$	$\star\star$	$\star\star$	$\star\star$	-	-

[a] Narrow c.m.s. energy spread arising from machine and beamstrahlung effects. $\star\star\star$ means the energy spread from the machine must be small ($\sigma \simeq \mathcal{O}(0.2\%)$); the luminosity spectrum must be well-measured (to the $\pm 0.1\%$ level); the last row of the table describes the performance quality of the detector for measuring the luminosity spectrum.

[b] By "Tracking" and "Calorimetry" is meant the measuring accuracy for momentum and energy, respectively.

[c] Small angle tagger would allow low-x studies and high Q^2.

would be discovered, and many standard analyses could be performed, for example the trilinear gauge couplings ($WWV, V{=}\gamma,Z^0$) measured about twice as precisely as at LEP2. Already at $\sqrt{s} \simeq 0.3$ TeV, the e^+e^- linear collider is unique in being able to cover all presently known $\mathcal{SUSY}$ Higgs models and, more generally, theories involving multi-Higgs doublets and singlets.

–At $\sqrt{s} \simeq 0.4$ TeV, the top threshold could be found with a binary scan involving 0.5fb^{-1}of data at each of ∼6 energies, or with a 2-3fb^{-1} run above threshold, to yield M_{top} to about ±2 GeV/c^2. The trilinear-gauge-coupling precision would improve by a factor of four relative to LEP2. The top threshold scan with 1fb^{-1}per point at 10 energy points, which could follow straight away or be delayed until later, would determine M_{top} to ±0.5 GeV/c^2. Now that the indirect knowledge (from e^+e^-) of the top quark has been comfirmed by the direct discovery (at the Tevatron), $\sqrt{s} \simeq$ 0.4 TeV would also be viable as first-stage energy of the machine.

–At the design goal of the first stage, with 10-100fb^{-1} of data at $\sqrt{s} \simeq 0.5$ TeV, many properties of the enigmatic top quark would be measured, M_{top} again to $< \pm 0.5$ GeV/c^2, the trilinear gauge couplings to about ±0.2%, and the Higgs bosons with masses up to ∼350 GeV/c^2 could be discovered. If light supersymmetry exists, depending on how it is realized in nature, this first stage could find some of the lighter supersymmetric particles ($\tilde{\chi}_j^{\pm}$, $\tilde{\chi}_i^0$, $\tilde{\ell}$).

⊙ – The second stage uncovers the new physics that lies at higher energies along with standard physics at those energies. The machine energy could be increased to successively higher values, with ∼100-200fb^{-1} of data to be taken at appropriate energies up to $\sqrt{s} \simeq$ 1-2 TeV. The goal would be to search for heavier Higgses and/or supersymmetric particles. The $\mathcal{SM}$ Higgs H_{SM} could be discovered up to a mass of $M_{\phi^0} \simeq 800$ GeV/c^2. If $\mathcal{SUSY}$ has been found earlier, the search for the heavier Higgs states (H^0 and A^0, produced in association, and $H^{\pm}$, produced in pairs) and the colored superpartners ($\tilde{g}$, $\tilde{q}$), which are heavy in most models will follow.

⊙ – Finally, if the Higgs turns out to be heavier than ∼800 GeV/c^2, it is no longer discoverable as particle, and the Higgs sector is strongly interacting. The programme for studying the mechanism of electroweak spontaneous symmetry breaking would consist of precision measurements of gauge boson production, e.g., the W_LW_L scattering experiment at the highest energy to which the machine could be upgraded. This again should probably be ∼1.5 TeV. At this stage, the e^+e^- linear collider will be the best place to measure new phenomena which may exist at such energies. Examples are the direct or indirect evidence for an extended-gauge Z', or the production of new heavy fermions if their masses are within the energy range of the collider. This highest energy question will be a topic for future workshops.

Complementarity of Hadron and e^+e^- Colliders

This point is addressed briefly here, since it touches the discussion several times in this chapter. It has been emphasized at the international workshops[1]-[11] that the pp and e^+e^- physics programmes are complementary, and what will have been found at the LHC will influence the experimental programme at the e^+e^- collider. Further examples of comparison of the physics potential of e^+e^- and pp colliders are found in Refs. [17], [18], and [19], and the most thorough examination to date is contained in the DPF study[11].

These studies show the complementarity of the e^+e^- machine to LHC is already important enough and sufficient to justify its construction at $\sqrt{s} \simeq 0.5$ TeV, which is a necessary technological step on the way to the higher energies; afterwards this complementarity shifts to other areas with the increase in $\sqrt{s}$ of the e^+e^- machine. For example the properties of a light Higgs would be measured at the first phase of the machine running at the peak of the Higgs production cross section, whereas an intermediate-mass Higgs would be measured at the second phase of the machine running at the appropriate energy. Most top quark properties will be derived from running at the peak of the $t\bar{t}$ cross section around 0.4 TeV. A similar strategy would be followed for the measuring properties of the supersymmetric particles and for mapping out $\mathcal{SUSY}$ parameter space: beam energy and polarization would be tailored to the measurement in question. If the new physics, now hoped for, were not to exist, the mechanism for $\mathcal{ESB}$ would be studied in W^+W^- production at 1.5 TeV and in precision measurements with polarized beams at lower energies.

So it is the capability to optimize the different measurements by running at low or high energies, with or without polarized beams, that gives the e^+e^- collider its full physics potential and full complementarity to the hadron colliders. It is well understood[17] that the discovery reach of the LHC is matched by the e^+e^- machine at the second stage of 1 to 2 TeV, and that this match is ultimately needed for more precise measurements of any new physics found there. But the experiments at lower energy are an essential part of the entire programme, so that a starting energy of $\sqrt{s} \simeq 0.4$-0.5 TeV is fully justified.

Finally, the e^+e^- and pp programmes not only complement each other, of course they overlap as well, and the crosschecks that emerge from the competing experiments will enrich the scientific understanding of the measurements.

Two Experiments, Two IRs

The reasons for needing at least two experiments are:

–scientific redundancy: particle-physics measurements must be done several times independently to ensure the result is correct;

–complementarity: with two detectors all requirements for e^+e^- in Tables 1 and 2

can be fulfilled;
–competition: the competition of physics ideas between several detector collaborations is an important stimulous for scientific progress;
–sociology: the constituency of particle physicists interested in e^+e^--physics is large enough for at least two collaborations.
–reliability: having at least two operational detectors will improve the overall machine-detector performance, since time lost for detector maintenance can be reduced.

Two experiments could of course co-exist in a push-pull fashion at one IR, which would mean less expensive construction costs for the collider but more expensive operating costs since the switchover time would take longer. Also, such a setup would put one experiment at a disadvantage with respect to the other.

Other advantages of having two or more IRs are:
–one of them could be equipped for the $\gamma\gamma$ and $e^-\gamma$ programmes;
–one of them could be equipped for machine development studies;
–especially attractive is the possibility discussed at LC95 of being able to switch between two IRs within a short time [20], which would clearly increase the flexibility of the facility and make it possible to serve two experiments with data in the same running period. Ideas for producing a collider facility with multiple IRs should be explored further [21].

The e^-e^-, $\gamma\gamma$, and $e^-\gamma$ colliders

These options allow complementary measurements to those of the e^+e^- collider. A few examples of standard physics and of new physics follow here and more in Appendix B. The reactions $e^-e^-\to e^-W^-\nu$, $\gamma\gamma\to W^+W^-$, and $e^-\gamma\to W^-\nu$ provide alternate ways of measuring the trilinear gauge couplings and thus yield sensitive tests of the $\mathcal{SM}$. Also all three collider modes offer alternate ways of producing supersymmetric particles, e.g., $e^-\gamma\to\tilde{e}\tilde{\gamma}$.

The e^-e^- collider gives access to possible exotic doubly charged objects, Higgses or dileptonic boson, and to possible discovery of a heavy Majorana neutrino. Since the e^-e^- collider requires only minor changes to the hardware of the e^+e^- machine and detector, its programme could be pursued during the first phase of the facility if there are strong physics arguments for it at that time.

A most important option, which should be a benchmark for feasibility studies of the $\gamma\gamma$ collider (see next subsection), is to use it for direct production of the Higgs boson, which proceeds via loops with contributions from new particles as well as from $t\bar{t}$ and W^+W^-. Thus a precision measurement of $\Gamma_{\gamma\gamma\to Higgs}$ gives indirect access to new physics.

The $e^-\gamma$ collider is the best conceivable machine for measuring the quark and gluon structure of the photon.

Z^0-pole running for physics

This option is discussed in Appendix C. The physics case might be made at some time to test sensitively the internal consistency of the $\mathcal{SM}$ with precision measurements at low energy, for example if no Higgs particle has been found up to $\sqrt{s}$ $\simeq$ 1 TeV. The luminosity requirement is $\sim 5 \times 10^{31} \mathrm{cm}^{-2}\mathrm{s}^{-1}$for Z^0-pole running for precision measurements using polarized beams. Both beams should be polarized to reduce the error on $\sin^2\theta_W$ to well below ± 0.0001. For experiments measuring CP violation in the b-quark sector or B_s^0 oscillations a luminosity of $\sim 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$would be needed.

Polarized beams

For the reason just given, for disentangling the γ and Z^0 contributions to the trilinear couplings, for the $g-2$ measurement of the top quark, for $\mathcal{SUSY}$ studies, to mention a few examples, polarized beams permit qualitatively new and important measurements to be performed. The SLC/SLD experience demonstrates that this technique opens new windows to precision measurements without excessive demands on luminosity.

$\mathcal{L}(\sqrt{s})$, the luminosity spectrum

Some physics studies require the highest possible luminosity, even at the cost of a larger machine-energy spread and significant beamstrahlung. But both machine-energy spread and beamstrahlung must be kept to a minimum for the top threshold scan, for an M_{Higgs} measurement, or for precision measurements of the trilinear gauge couplings, among other things. The ideal linac will operate in both a high-luminosity mode and in a narrow machine-energy-spread mode. In the latter mode the machine-energy spread should be of order 0.2% (standard deviation) or less, and the detector for measuring $\mathcal{L}(\sqrt{s})$ will need good endcap tracking so that the luminosity spectrum can be known to a matching precision of $\pm 0.1\%$ (see last row of Table 2) [22].

Z^0-peak running for calibration

Running at the Z^0-peak would be of great help for the calibration of the detectors, but only about 3 pb^{-1} of data is enough per calibration run, of which about three per year would be needed. Thus a luminosity of $\sim 10^{31} \mathrm{cm}^{-2}\mathrm{s}^{-1}$is sufficient for this purpose.

2.6.5 IR and Detector

Issues for which the machine and detector closely interact are discussed, and quantities affecting the detector design follow in Tables 3 and 4.

The machine parameter lists from LC95 [16] were used by Daniel Schulte/DESY to derive an internally consistent set of figures for luminosity and background. That is, the same set of Monte Carlo programs was used to calculate the numbers for all machines, so that a relative comparison of conditions at the experiment due to machine effects is possible. In Chapter 1 of this report, luminosity and background figures from analytic formulae by Pisin Chen/SLAC were used. The absolute accuracy of the numbers in the tables will be the subject of further study. Those in Table 3 related to luminosity from the Monte Carlo tend to be larger than the ones from the analytic calculation, but agree to 30% or better in most cases. The figures in Table 4 related to backgrounds due to minijets are different from those of the analytic formulae because of the addition of the direct process and the once-resolved process (describing the interaction of virtual quarks or gluons from one photon with the photon from the other beam) in the Monte Carlo. By and large the Monte Carlo and analytic calculations always agree within a factor of two.

Backgrounds

The sources of background are synchrotron radiation and debris from the final quads, muon backgrounds arising from upstream sources, e^+e^- pair creation in the field of the colliding bunches, and hadrons produced by collisions of real or virtual photons from beamstrahlung or initial state radiation. Synchrotron backgrounds are typically produced by particles in the beam tails which radiate photons in the latter sections of the final focus (FF) which strike the tip of the last quadrupole. These backgrounds can be controlled by scraping beam tails in the post-linac collimation section. The muon background which results from this collimation is controlled by the big bend and by a number of spoiler magnets which fill the transverse dimensions of the tunnel. The majority of e^+e^- pairs from beam-beam effects are produced at small angles to the beam axis, with a transverse momentum and angle determined by the beam size and intensity. Their angular distribution defines a so-called dead cone which must be covered by a mask. While the machine design should minimize this cone, the mask should be instrumented with an e^+e^- pair monitor, which can provide information about the size of the luminous region, and small angle bhabha (luminosity) monitor. The detailed design of the masks, detectors, the aperture of the exit quadrupoles, and the value of the beam crossing angle determine how many backscattered pairs will reach the detector. In Table 3 values for crossing angle, dead cone (for 2T magnetic field, 0.5m to mask), collimation, drift to IP, and aperture of quadrupoles are listed.

Beam parameters at the interaction point (IP) control the number of primary e^+e^- and hadrons pairs produced at inherently large angles. Table 4 compares backgrounds per bunch crossing and the backgrounds for the example of a sub-detector integrating over 100ns. The number of particles ($e^{\pm}$) from beam-beam effects are seen in rows 6 and 9 of Table 4, and those for hadronic events produced in two-photon reactions are in rows 7,8 and 10,11. The actual backgrounds of $e^{\pm}$ reaching the detector are suppressed by the magnetic field; the average energy of the particles listed in rows 6 and 9 is only 100 MeV, independent of machine design.

Vibrations

All machine designs, whether at 0.5 or 1.0 TeV, require beam stability at the sub-10 nm level to achieve their design luminosities, as can be seen in the values for the spot-height σ_y in Table 3, row 8. Ground vibration, of either seismic or cultural origin, must be controlled to well below this level at the FF. After site selection, mechanical means must be used to reduce vibrations at frequencies greater than those which can be corrected by beam-based feedback. Active devices which feedback signals measuring absolute or relative quad motion are under investigation; if successful in principle, they must be engineered into the detector environment. The passive device most frequently suggested to date is a support tube linking the quads on either side of the IP. The size and mass of such a tube, the weight of the masks and quadrupoles it must support, and the consequences to detector access must be considered. However, it would be better for the experiment if a way could be found to avoid this tube, which would add additional scattering material inside the detector volume. Detector and FF quad cooling and gas systems must be designed which do not introduce any additional vibrations.

Beam diagnostics near the IP

It is important to be able to measure the beam parameters at the IP separately for each beam at the full beam intensity. Physical wires will not survive; current designs for optical wires or interferometers will not work at wavelengths less than about 10 nm. Thus R&D to produce such devices and locate them within 20% of the distance from the IP to the first quad is needed and will require close cooperation between detector and machine physicists.

Extracted beam diagnostics

Experience from the SLC/SLD tells us that these entail an energy spectrometer, a compton polarimeter, and beamstrahlung photon monitor. Initial design work, as elaborated on later, should begin as soon as possible.

$\gamma\gamma$-collider implications

The laser photons must be transported to within a few centimeters of the IP for Compton backscattering and the electrons must be extracted without creating too much background. The interaction among these devices, the vertex detector, the other beam monitoring equipment, and the masks is sufficiently complicated so as to require the design of a dedicated detector for the $\gamma\gamma$ experiments at a dedicated IR. Conceptual engineering solutions have not yet begun to address these issues. Since e^-e^-, $\gamma\gamma$, and $e^-\gamma$ colliders are addressing similar physics questions to e^+e^-, it is possible that the outer detector for an e^+e^- experiment with a modified inner detector would be suitable.

Detector timing

The bunch time structure of the various designs varies from 0.67 ns (CLIC) to 1000 ns (TESLA), as seen in Table 3, row 7. Through the beam-beam interaction, each bunch crossing occuring within the time resolution of the detector may produce particles that can partially obscure a real physics event triggered by a different bunch in the train. Or, the background event may itself produce a non-physics junk trigger (as dealt with in the next section). Thus, the time resolution of the detector and the maximum tolerable trigger rate become potentially important parameters in deciding between competing machine designs. If sub-nanosecond timing were trivial and computing power large, fast, and cheap enough, any machine bunch structure could be considered. Unfortunately, such is not the case. While sub-nanosecond timing has been achieved in various detectors, it is typically not trivial and not available in real-time. Proponents of machine designs requiring fast, high resolution detectors must begin realistic conceptual detector designs as soon as possible, or demonstrate that the backgrounds do not adversely affect their analyses. Table 4, row 11 gives a measure of the probability of having stiff particles from underlying hadronic events in a good physics event for a detector with a typical timing resolution of 100 ns. The situation degenerates beyond that described in Table 4 if the bunch spacing and crossing angle are not sufficient to prevent the interaction of incoming bunches which have passed the IP with outgoing bunches yet to arrive at the IP, which may be the case for the CLIC design.

Trigger rate and Data volume

At the SLC/SLD the trigger rate and data volume can vary enormously from pulse-to-pulse. Overall trigger rates under poor conditions are much larger than can be explained by physics or simulated backgrounds. Typically they are ascribed to abnormal and atypical behavior of some part of the accelerator. While one hopes that any future collider will be immune to such problems, it is prudent to

design the trigger and data aquisition with sufficient dynamic range to ride out these disturbances. Additionally, it has been found that the detector often provides some of the most useful diagnostics for the accelerator. The ability to easily correlate its data with that of the machine should be a design consideration.

All the machine designs except VLEPP incorporate multibunch operation. When the interbunch spacing is long enough to allow for a trigger decision, one can imagine schemes where the rate of the first-level trigger would be the product of the average bunch-crossing rate (Table 4, row 12) and the probability for a hadronic background event from the beam-beam interaction (Table 4, row 7). The resulting trigger rate (Table 4, row 13) can be compared, for example, with the LEP first-level triggers.

When the interbunch spacing is very short, it makes more sense to consider a simple bunch train crossing as first level trigger [4]. This would be followed by a software trigger that analyzed all data buffered into memory during the bunch train. In this model, the maximum trigger rate would be the machine repetition rate, as tabulated in Table 4 row 14. For comparison, Table 4 row 15 shows the rate for useful physics events, assuming 20pb as a rough idea of the cross section.

There are different ways to imagine the architecture for the trigger and data acquisition system as indicated above, and some combination of hardware and software triggers can be adapted to the time structure of the machine that is ultimately built. The system would consist of buffering the frontend signals in pipelines at a rate related to the instantaneous bunch-crossing rate (see *Detector timing* above) along with hardware triggers to pick out which locations in the pipeline should be transferred to memories for the last-level software trigger. Rows 12 and 13 indicate that hardware triggers can reduce by an order of magnitude the number of locations in the pipeline that have to be transferred.

Finally, a guess at the data volume can be made using row 15 (the 20pb rate). Extrapolating from LEP/SLC experience, a good event might contain a few megabytes of information [4].

Table 3: Table of some machine parameters related to IR and detector design.

	TESLA	SBLC	JLC(S)	JLC(C)	JLC(X)	NLC	VLEPP	CLIC
[Units in brackets]	Upper numbers for 0.5 TeV$\equiv\sqrt{s_0}$ machine version Lower numbers for 1.0 TeV$\equiv\sqrt{s_0}$ machine version							
1)$\mathcal{L}$ (with pinch)	6.0	3.9	4.6	9.3	5.1	6.9	3.9	1.0-4.5
$[10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	10.1	6.3			9.6	14.1		2.2-9.7
2)$\int \mathcal{L}dt/_{\mathrm{y}=10^7\mathrm{s}}$	20	13	15	31	17	23	13	3-15
$\times$33%eff.$[\mathrm{fb}^{-1}]$	33	21			32	46		7-32
3)δ_B (due to beamstr.)	2.9	3.1	8.2	4.9	3.0	2.5	11.0	3.6
[avg.beam en.loss in %]	2.4	6.5			7.5	7.1		7.3
4)$\mathcal{L}$ ($\sqrt{s}>0.99\sqrt{s_0}$)	3.4	2.1	1.7	4.4	3.2	4.3	0.8	0.5-2.4
$[10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	6.4	2.2			4.4	5.9		0.8-3.6
5)Bunches/train	800	125	50	72	85	90	1	1-10
	4180	50			85	75		1-10
6)Trains/sec	10	50	50	150	150	180	300	2530-1210
	5	50			150	120		4000-1800
7)Interbunch spacing	1000ns	16ns	5.6ns	2.8ns	1.4ns	1.4ns	3.3ms	0.67ns
	200ns	10ns			1.4ns	1.4ns		0.67ns
8)σ_x/σ_y-spot size	1000/64	670/28	260/3.0	260/3.0	260/3.0	320/3.2	2000/4	250/7.5
[nm]	325/8	572/9			191/2.2	357/2.3		200/6.0
9)σ_z-spot size	1000	500	120	120	90	100	750	200
$[\mu\mathrm{m}]$	500	500			81	100		200
10)pb^{-1}/bunch	7.5	6.3	18.2	8.6	4.0	4.3	131.	3.8
$[10^{-7}\mathrm{pb}^{-1}]$	4.8	25.2			7.5	15.7		5.4
11)Crossing angle	0	3	6.4	6.0	6.1	20	6	1
[mrad]	0	3			5.0	20		1
12)Detector dead cone	79	83	120	97	85	81	124	66
(2T,0.5m to mask)[mrad]	65	85			89	107		70
13)Collimation $n\times m$	12x38	7x7	6x35	6x35	6x35	10x40		6x13
$[n\sigma_x\times m\sigma_y]$								
14)$\ell^\star$ (drift to Q01)	3.0	2.0	2.5	2.5	2.5	2.0		1.25
[m]								
15)a (ϕ aperture of Q01)	48.	8.	13.7	13.7	13.7	10.		12.
[mm]								

Table 4: Table of some machine parameters related to backgrounds.

	TESLA	SBLC	JLC(S)	JLC(C)	JLC(X)	NLC	VLEPP	CLIC
[Units in brackets]	Upper numbers for 0.5 TeV machine version Lower numbers for 1.0 TeV machine version							
1)$N_e\pm$ per bunch	5.1	2.9	1.44	1.0	.63	.65	20	.8
$[10^{10}]$	.9	2.9			.62	1.1		.8
2)$\gamma\epsilon_x/\gamma\epsilon_y$	20./1.	10./.5	3.3/.045	3.3/.045	3.3/.045	5./.05	20./.075	3./.15
$[10^{-6}$m rad$]$	5.2/.063	10./.1			3.3/.045	5./.05		3.9/.2
3)β_x/β_y at IP	24.5/2.	22./.8	10./.1	10./.1	10./.1	10./.1	100./.1	10./.18
[mm]	20./1.	32./.8			11./.1	25./ .1		10./.18
4)$N_{beamstr.\gamma}$per $e^{\pm}$	2.6	2.0	1.8	1.3	.9	.8	4.8	1.4
	1.2	2.2			1.1	1.2		1.7
5)$\langle E_{beamstr.\gamma}\rangle$	2.9	3.9	11.3	9.3	8.6	7.3	5.6	6.3
[GeV]	9.5	14.5			33.	29.		22.
Backgrounds/bunch								
6)$N_{beamstr.e\pm}$/bunch	31	18	37	15	6	6	625	7
θ >150mrad, p_T >20MeV/c	8	53			10	21		10
7)Hadr.ev. per bunch	.15	.10	.33	.13	.05	.05	2.7	.05
$E_{\gamma\gamma-c.m.s.}$ $\geq$5GeV	.09	.60			.19	.34		.13
8)Minijet ev. per bunch$[10^{-2}]$	.32/.016	.26/.014	1.9/.10	.52/.03	.16/.009	.13/.007	14./.71	.15/.009
p_T^{min}(GeV/c)= 3.2 / 8	.41/.022	4.4/.23			2.0/.10	3.1/.16		1.2/.063
Backgrounds/100ns								
9)$N_{beamstr.e\pm}$/100ns	31	112	661	536	429	429	625	7-70
θ >150mrad, p_T >20MeV/c	8	530			714	1500		10-100
10)Hadr.ev./100ns	.025	.16	1.3	.50	.70	.52	.69	.05-.11
per unit lumi$[10^{33}\text{cm}^{-2}\text{s}^{-1}]$	.009	.95			1.4	1.7		.06-.13
11)Minijet ev./100ns	.003	.016	.33	.18	.11	.09	14.	.002-.015
p_T^{min}=3.2GeV/c	.004	.44			1.4	2.2		.012-.12
Rates								
12)$\langle$Bunch crossing rate$\rangle$	8.	6.25	2.5	10.8	12.75	16.2	.3	2.53-12.1
[kHz]	20.9	2.5			12.75	9.		4.-18.
13)$\langle$Hadr.ev. rate$\rangle$[kHz]	1.2	.6	.8	1.4	.6	.8	.8	.1-.6
$E_{\gamma\gamma-c.m.s.}$ $\geq$5GeV	1.9	1.5			2.4	3.1		.5-2.3
14)Train crossing rate	10	50	50	150	150	180	300	2530-1210
[Hz]	5	50			150	120		4000-1800
15)1 event/20pb rate	.12	.08	.09	.18	.11	.14	.08	.02-.09
[Hz]	.20	.13			.19	.28		.04-.19

2.6.6 Detector Options

To summarize the discussion up to now, the physics implications on the detector design are listed in Tables 1 and 2 above, and the effects of the different machine designs on the IP and detector design are given in Tables 3 and 4 above. Here, some performance figures of detectors used in simulations for workshops [4, 22, 23, ?, 25, 26, 27, ?, 29, 30, 31, ?, 33, 34, 35, ?, 37, 40, 41, ?, 43, 44, 46] are listed in Table 5.

Earlier studies have shown that the performance of existing e^+e^- detectors would be good enough to do much of the physics in the early phase of the machine at low energy. Typical performance figures are shown in the first three columns of Table 5. For higher luminosities and/or higher energies, high performance detectors are needed, and such detectors are the subject of the last two columns. Examples given are the "JLC Detector" [4] which is being designed at KEK and the "1 TeV Detector" [44] suggested in Europe. The JLC Detector is conceived to have good hermeticity over the fullest possible solid angle, to have jet invariant mass resolution comparable with the natural widths of the $W^{\pm}$ and the Z^0, and give a lepton pair recoil mass resolution for $e^+e^- \rightarrow Z^0 H_{SM}$ comparable with the beam energy spread of $\sim$200 MeV. The 1 TeV Detector is being designed with the demands on performance listed in Tables 1 and 2 in mind. Both detectors are large and give good performance at the higher energies of the second phase of the machine. An alternative would be a small high-field detector [37, 46]; the details of such a detector have not yet been worked out.

Table 5: Examples of detector performances used in physics studies.

	LEP/SLC-Style	ee500 1991	ee500 Typical	JLC Detector	1 TeV Detector	units
Tracking $\frac{\delta p_t}{{p_t}^2} = C$						
$C =$	8	5-100	10	1	2	$\times 10^{-4}$GeV/c^{-1}
E-M Calorimeter $\frac{\delta E}{\sqrt{E}} =$	0.2	0.02-0.15	0.1	0.15	0.10	$\sqrt{GeV}$
Hadronic Calorimeter $\frac{\delta E}{\sqrt{E}} =$	0.9	0.3-1.0	0.8	0.40	0.65	$\sqrt{GeV}$
Energy Flow $\frac{\delta E}{\sqrt{E}} =$	0.65	0.3-0.8	0.5	0.3	0.4	$\sqrt{GeV}$
Vertexing $\delta(IP) = A \bigoplus \frac{B}{p}$						
$A =$	25	5-20	10	11	10	μm
$B =$	100	50-100	50	28	50	μmGeV/c
Hermetic coverage $\lvert\cos\theta\rvert <$	0.96	0.70-0.99	0.95	0.98	0.98	

2.6.7 Tabulation of What Has Been Done

Backgrounds	
$e^{\pm}$ pairs	-ABEL runs into JLC and LEP/SLC-like detector (T.Tauchi) using EGS/GEANT (G.Punkar, D.Schulte).
	-Interface ABEL to GEANT with SLC/LEP-type detectors (M.Ronan, D.Schulte).
Synchrotron rad. from Q's	-QSR program vectors → IP (T.Tauchi) → detector using EGS(G.Punkar, D.Schulte).
Muons	-Feldman MarkII muon transport code run on NLC/JLC/TESLA beam lines → "big bend" and collimators to reduce flux (L.Keller, Y.Namito, M.Sachwitz, J.Schreiber).
Programs	
Beam-beam effects with $e^{\pm}$ pair creation	ABEL (K.Yokoya, P.Chen, T.Tauchi)
	MACPAR+TRACKIT (S.Ritter, D.Schulte)
	GUINEA PIG (D.Schulte)
	RBEAM with no pairs (L.Wood, O.Napoly, P.Pierini, D.Schulte)
Minijets	Minijet (P.Chen, T.Barklow)
	GUINEA PIG (D.Schulte)
	MINIJET (A.Miyamoto, H.Hayashii)
Synchrotron rad.	MQRAD (T.Morimoto, T.Tauchi)
	SLAC QSR (S.Hertzbach)
Muons	MU-CARLO (G.Feldman, S.Rokni)
	MUON89 (W.R.Nelson) - analytic calculation
Vibrations	
Ground measurements	done at SLAC,DESY,KEK,CERN, Finland and Sazare(Japan).
Support tube	design and calculations (SLAC, KEK, DESY)
Beam spot size (nm)	
	Laser interferometer (T.Shintake)
	$e^{\pm}$ pair monitors (T.Tauchi, P.Chen)
	Beamstrahlung photon monitor (D.Schulte)
	IP-BPM (T.Shintake)
	Nanometer RF BPM (S. Hartman)

2.6.8 Other Things Left to Do

Vibrations

Measurements of Ground Motion

Current measurements of ground motion have concentrated on the frequency

dependence of the displacement power spectrum and the normalized correlation function relating the coherence of motion between two detectors separated by a given distance. We now understand that the quantity most useful as input to the calculation of tolerances for a given linac or final focus lattice is the power spectum $S(f,k)$ as a function of both frequency f and wave number k, measured in units of 1/distance. This function contains all spatial and temporal correlations. Current tolerance estimates use semi-empirical formulae to relate frequency and wave number.

$S(f,k)$ should be measured at a quiet, a moderate, and a noisy site, tabulated, and made generally available. The emphasis should not be on supporting one particular site over another, but on pointing out the sensitivity of each machine design to the problem. Currently the devices used for these seismic measurements compare two absolute measurements of motion. Arrays of devices which can accurately measure the *differences* in motion may need to be developed.

Additionally, as most of the power in seismic events is carried within one wavelength of the surface in so-called Raleigh waves, the general dependence of $S(w,k)$ as a function of depth should be made. Moreover, the tunnel itself may serve to influence the propagation of waves impinging on it from an otherwise homogeneous material. Studies, whether by simulation or measurement, of how this may affect the overall problem of ground motion should be carried out.

Engineering of Supports

Supports for magnets, rf structures, and the detector should be designed which do not amplify the effects of seismic or cultural noise. The concept of the support tube linking both ends of the final focus needs to be more adequately developed. Insufficient engineering has been done to indicate what the size and mass of such a tube must be to provide stability against relative motion of both sides of the FF quads. If indeed necessary it would limit access, add mass, and, if not carefully supported, it could translate low frequency seismic noise to the higher frequencies of its normal modes where it would be more difficult to control with feedback.

Active and Passive Vibration Suppression

Tests which attempt to feedback seismic signals to piezoceramic actuators in a closed feedback loop have begun at SLAC, KEK, and DESY. Early results show a factor of three reduction in rms jitter in the 1-10 Hz frequncy range. More work to develop systems with higher attenuation is necessary. This may require the development of devices to measure the exact quantity of interest for beam stability. For example, using a geophone to measure the motion of a magnet might be less desirable than measuring the change in field that the beam sees as a result of such

motion. If correlated motion between two magnets is driving luminosity loss, then perhaps devices which accurately measure the relative motion of the two magnets need to be developed. One would not feel confident until at least a factor of ten safety margin exists in the frequency range not covered by beam-based feedback.

Engineering efforts for structure or magnet mounts might include passive damping if such a system did not compromise the long term stability of the machine alignment. Investigations into elastic materials or to the effects of trenches to isolate structure from shallow ground waves of high frequency may be in order.

Beam-Based Feedback as a Vibration Suppression Tool

Current estimates of the efficacity of beam based techniques to control vibrations are based on models of the SLC feedback system extrapolated to the bunch frequency of the new machines. Estimates based on actual SLC performance should be carried out.

Analysis of the Spent Beam

Beamstrahlung at the IP will shift the mean energy and introduce a large energy spread when the beams are in collision. When the beams are not in collision they will have their full energy and narrow width. Beam dump devices such as the energy spectrometer and Compton polarimeter must be built in such a way as to be able to make measurements under both conditions. Already at SLC, the beamstrahlung photon background makes these measurements difficult. Designs which can handle the increased photon background of the higher energy colliders must be developed. Depolarization of the electron beam due to the spin-flip (Sokolov-Ternov) effect in the field of the opposing beam is expected to be about 0.4% at 0.5 TeV and go up to about 5% at 1 TeV. A system of pre- and post-collision polarimeters may be required to understand the polarization completely.

Conceptual designs exist for using the distribution of electron pairs produced by the beam-beam interaction as a diagnostic tool. The practical design of detectors which can survive the radiation environment and readout in the multibunch environment of the machines should be developed.

Background Studies

Studies which incorporate the tracking of secondary particles from beam-beam interaction pairs into vertex detectors have begun. More elaborate simulations which model realistic detectors, and which allow events from the physics generators to be overlaid, must also begin. Discussions of machine design would be facilitated if these simulations were in some sense generic. That is, machine design comparisons will be more meaningful if the simulations use a single model detector and physics generator,

a common program to calculate the beam-beam backgrounds, and a mutually agreed upon benchmark physics process.

2.6.9 Summary and Recommendations

One concludes from the discussion on Tables 1 and 2 above and in the Appendices that:
$\odot$ – the lowest energy of the machine should overlap with the highest energy of LEP so that no e^+e^- "discovery/measurement gap" exists;
$\odot$ – the first stage of the collider should be $\sqrt{s} \simeq 0.5$ TeV, which opens much of the physics potential listed in Tables 1 and 2, allows precision measurements of the $\mathcal{SM}$ and perhaps discovery of the Higgs and/or $\mathcal{SUSY}$ and provides a physics programme complementary to hadron colliders;
$\odot$ – the machine design should include an upgrade path to $\sqrt{s} \simeq 1$ - 2 TeV in order to match the discovery reach of LHC, to discover/measure any new physics in this energy regime, and to study $\mathcal{ESB}$ in the heavy Higgs case;
$\odot$ – the luminosity required is $\int \mathcal{L}dt$ up to 100fb^{-1}/year for precision measurements;
$\odot$ – polarized beams open new physics windows and are necessary: polarized e^- are essential, polarized e^+ will improve the power of this technique; and
$\odot$ – Z^0-peak running with polarized beams offers the possibility for sensitive new tests of the internal consistency of the $\mathcal{SM}$.

The series of physics milestones between LEP energies and $\sqrt{s} \simeq 1$ TeV show that a convincing physics case can be made for commissioning the machine at lower luminosity ($10^{33}\text{cm}^{-2}\text{s}^{-1}$) and a c.m.s. energy of 0.3 to 0.4 TeV before reaching the first stage energy of $\sqrt{s} \simeq 0.4$ to 0.5 TeV. The combination of experiments with polarized beams and attainment of the design luminosity (a few $\times\ 10^{33}\text{cm}^{-2}\text{s}^{-1}$) would round out a physics programme that would span several years. The second stage will continue with a step-wise energy increase up to $\sqrt{s} \simeq 1$ - 2 TeV. Both stages contain important ingredients of the complementarity and competition to the hadron colliders.

How the increase to 1 TeV or higher is realized is a question generating considerable discussion and leading to several options: increase the accelerating gradient, increase the length of the machine, change the technology, or a combination of these. The final design report for the 0.5 TeV machine should include a viable strategy for such an energy increase, which of course could change after the experience with the first-stage running is gained.

In the event that no light Higgs boson has already been found before the linear collider is built, then the decision to build the $\gamma\gamma$ option can be left until after the physics results have been extracted from the 0.5 TeV e^+e^- running – as can decisions

about energy upgrades or running at the Z^0-pole. The modifications needed for the e^-e^- collider seem to be modest, so that this running could follow at any time the physics case warrants it.

The detectors are more challenging that those for LEP/SLC, though easier than for hadron colliders. There seems to be no critical aspect of the detectors which would tell us that any one of the machine designs would preclude achieving the physics goals set forth. For the hardware, larger beam spots make mechanical problems easier to solve. For the physics analyses, a larger bunch-crossing time reduces the effects of underlying events. The backgrounds for the different machines are similar and will be larger than at LEP, but not so large as to spoil the cleanliness of e^+e^- experimentation as experienced in the past.

Considerable R&D work related to IR issues must be done, as discussed in subsection 6 above; it is mainly related to elimination of vibrations and to a better understanding of backgrounds.

Appendices

A The e^+e^- Linear Collider Experimentation

Tables 1 and 2 of the subsection on main e^+e^- physics topics serve as a guide to the interplay between physics requirements, machine parameters and detector performance for the e^+e^- collider. In this appendix some details of the reasoning leading to those tables are discussed.

The list of physics topics and their implications is the result of many international workshops on e^+e^- physics beyond LEP2 – La Thuile[1], SLAC[2], Snowmass[3], Japan[4, 13], Europe[5, 9, 10, 12], Finland[6], the USA[7, 11], and Hawaii[8], among others – and from the workshops on the machine technology: LC88 at SLAC, LC90 at KEK, LC91 in Protvino, LC92[14] in Garmisch-Partenkirchen, LC93[15] at SLAC, and LC95 at KEK[16].

A.1 Overview

Examples of the main **e^+e^- physics goals** cited in Tables 1 and 2 are:
• Higgs bosons: discovery and exploration of Higgs bosons (via Higgs-strahlung and gauge-boson-fusion) and of associated production in the case of the minimal $\mathcal{SUSY}$ model ($\mathcal{MSSM}$); measurement of the spin-parity quantum numbers and of the branching ratios in order to test the theory (e.g., to distinguish between $\mathcal{SM}$ and $\mathcal{MSSM}$ Higgses).
• W_LW_L-scattering: in the heavy Higgs scenario, study the mechanism for $\mathcal{ESB}$ through measurement of W_LW_L-scattering at the highest possible energy if no light

Higgs is found.
• Supersymmetry: search for signals of charginos, neutralinos, sleptons, as well as of squarks and gluinos; if discovered, extraction of the mass spectrum, the widths and the couplings; measurement of the $\mathcal{SUSY}$-model parameters to understand the mechanism for supersymmetry breaking.
• Extended-gauge models: discovery limits for new gauge bosons and new matter particles.
• Gauge bosons: measurement of the trilinear couplings, of the quadrilinear couplings; unfolding the γ and Z^0 couplings with polarized-beam experiments.
• Top quark: measurement of M_{top} at and above threshold, of the top quark magnetic and electric dipole moments, of its decay properties, of the Yukawa coupling, and of rare decays.
• Quantumchromodynamics: measurement of $\alpha_s(s)$, many studies of the hadronic final state.
• Two-virtual-photon collisions: systematic study of QPM-QCD ("minijet") phenomenology; measurement of the photon structure function $F_2^\gamma(x, Q^2)$, and of inclusive resonances and heavy-flavor production.

The global **machine** aspects of interest listed in Tables 1 and 2 are: luminosity, $\sqrt{s} \equiv$ c.m.s. energy, $\mathcal{L}(\sqrt{s})$ spread, and beam polarization. In this evaluation one assumes that both beams are polarized. Narrow $\mathcal{L}(\sqrt{s})$ means the energy spread from the machine must be small ($\sigma \simeq \mathcal{O}(0.2\%)$) and the luminosity spectrum well-measured (to the $\pm 0.1\%$ level).

The **detector** perfomance has the following general breakdown in Tables 1 and 2: hermetic coverage, tracking ($\frac{\delta p_t}{p_t{}^2}$), calorimetry ($\frac{\delta E}{\sqrt{E}}$), three diminsional (3-D) granularity of the subdetectors, charged lepton identification (and sign determination), vertex tagging, and π/K identification. Table 5 lists the performance used in physics simulations for the international workshops [4, 22, 23, ?, 25, 26, 27, ?, 29, 30, 31, ?, 33, 34, 35, ?, 37, 40, 41, ?, 43, 44, 46].

A.2 The Evaluations in Tables 1 and 2

The basis for the $\star$-ratings, which are being continually updated, is illustrated with a few examples.

• The Higgs boson

In the $\mathcal{SM}$ there exists a single CP-even scalar boson H_{SM}. In the $\mathcal{MSSM}$ the physical spectrum consists of three neutral bosons, the CP-even h^0 and H^0 and the CP-odd A^0, and a pair of charged bosons $H^\pm$. The searches for these particles

have been simulated in quite some detail using the performance of existing detectors [23, 26, 32, 35, 40, 49], and the discovery with such detectors is straight-forward in the light-Higgs scenarios studied up to now (i.e., for Higgs masses up to about 350 GeV/c^2 at $\sqrt{s} \simeq 0.5$ TeV). Vertex tagging improves the significance of the signals considerably and is thus rated highly, in particular if $M_{Higgs} \simeq M_{Z^0}$[32]. Excellent tracking improves the M_{Higgs} determination [4]. Hermeticity is needed to identify decays with large missing energy and therefore might help to distinguish between $\mathcal{SM}$ and $\mathcal{MSSM}$ since the $\mathcal{MSSM}$ Higgses can possibly decay invisibly. While light Higgses can be discovered with detectors of a performance similar to LEP and SLC detectors, the measurement of a heavier Higgs at higher $\sqrt{s}$ requires a detector with improved resolution as indicated in Table 5.

High luminosity is needed to measure the Higgs branching ratios [35]. A higher c.m.s. energy and luminosity are required in case the $\mathcal{SM}$ Higgs is heavy; the H_{SM} could be discovered up to a mass of $M_{\phi^0} \simeq 800$ GeV/c^2 [36]. Higher luminosity and $\sqrt{s}$ are also needed if the world is supersymmetric, since then the Higgs masses range from light (h^0) to possibly very heavy (H^0,A^0) and the charged Higgs ($H^{\pm}$) may also be heavy. In addition to Higgs-strahlung, the neutral $\mathcal{SUSY}$ Higgses are produced in association and the charged Higgs is pair-produced.

As stated earlier, already at $\sqrt{s} \simeq 0.3$ TeV, the e^+e^- linear collider is unique in being able to cover all presently known $\mathcal{SUSY}$ Higgs models and, more generally, theories involving multi-Higgs doublets and singlets.

• W_LW_L scattering

If $M_{Higgs}$is larger than ~800 GeV/c^2, the Higgs is strongly interacting and no longer discoverable as particle, and the programme for understanding the mechanism of electroweak spontaneous symmetry breaking would consist of precision measurements of gauge boson production, the W_LW_L-scattering experiment [28, 43], at the highest energy to which the machine could be upgraded, which should be at least 1.5 TeV.

• Supersymmetry

The lightest supersymmetric particle (LSP) is often assummed to be the lightest neutralino $\tilde{\chi}_1^0$ and stable. It is weakly interacting and frequently an end-product in reactions producing supersymmetric particles. Thus topologies involving $\mathcal{SUSY}$ particles are often characterized by missing energy, so that hermeticity of the detector is essential for these measurements. On the machine side, beam polarization will help for the searches, since for example *slepton* production is enhanced while the W^+W^- background is supressed. If $\mathcal{SUSY}$ is discovered, beam polarization becomes a very important tool for measuring its properties [33], and very good

three-dimensional granularity of the detector makes the studies of the complicated final states more tractable. In many $\mathcal{SUSY}$ models, the non-colored states (chargino $\tilde{\chi}_j^{\pm}$, neutralino $\tilde{\chi}_i^0$,slepton $\tilde{\ell}$) are light and might be produced at the 0.5 TeV phase of the machine, while the colored states (squark $\tilde{q}$, gluino $\tilde{g}$) tend to be heavy so that higher energies would be needed to study them.

• Extended gauge models

Extended gauge models almost always require higher energies, higher luminosities, and the best possible detectors. If a Z' exists, or new heavy fermions, the linear collider is ideally suited to investigate these objects. For these studies the highest energy of the e^+e^- collider should be realized, $\sqrt{s} \simeq 2$ TeV, and the discovery reach of the LHC will be exceeded by virtual Z' production in e^+e^-[11].

• The electroweak gauge bosons

The golden channel the measurement of anomalous $W^{\pm}$ couplings ($WWV, V = \gamma$,Z^0) [28, 31] is $e^+e^- \to W^+W^- \to \ell\nu\bar{q}q'$. Detector aspects for the measurement of anomalous $W^{\pm}$ couplings are discussed in Ref.[41]. Hermeticity is important because of the energetic neutrino in the final state. The LEP/SLC-type detectors are adequate for extracting the couplings at $\sqrt{s} \simeq 0.5$ TeV [28], but detectors as studied for JLC [4] and for 1 TeV [44] improve the small-angle tracking performance, which is valuable due to the forward-peaking of the production angular distribution. These detectors allow good tracking down to $|\cos\theta| < 0.98$ for the helicity analyses. At higher energies, the improved tracking performance is necessary.

A well-measured luminosity spectrum, polarized beams, high luminosity and higher energy are important machine aspects. The error in measuring the trilinear gauge couplings decreases roughly as $1/s$, so that higher energies are preferable [28] for this measurement, along with the corresponding increase in luminosity. Beam polarization is of great help in disentangling the γ and Z^0 couplings.

• The top quark

The study of the top quark is one of the central research topics at the linear collider [30]. The demands on the collider performance will be different for the two energy-regions in which top-quark studies will be done: at the threshold of $t\bar{t}$ production and at the maximum energy of the collider. In both cases the majority of $t\bar{t}$ events will have a characteristic six-jet structure coming from the prompt decay of each t-quark into a b-quark and a W-boson. Monte Carlo studies show that these events will be efficiently separated from backgrounds.

The measurement of the top mass in the *threshold region* is particularly exacting. The $t\bar{t}$-threshold scan will be a distinct and important part of the early programme

of the collider's first phase, and it is important that the linac design be capable of operating in the required low-momentum-bite, low-beamstrahlung mode at around 0.35 TeV, for which the machine parameters may need reoptimization. Thus one needs to know what beamstrahlung spectrum a luminosity of $10^{33} cm^{-2} s^{-1}$ and a machine energy spread of $\sigma \simeq 0.2\%$ would yield. Equally important for the accuracy with which the top mass can be determined is the precision measurement of the luminosity spectrum $\mathcal{L}(\sqrt{s})$ to an accuracy of $\pm 10^{-3}$. This requires good tracking in the endcap region of the detector [22], as indicated in the last row of Table 2. top quark mass, so that a precision of better than $\pm$500 MeV/c^2 can confidently be predicted from a 10 fb^{-1} scan. This provides a crucial extra input to the fits of the standard model parameters which can be used to constrain the Higgs boson mass. In this case, the light Higgs boson mass can be restricted to $\leq$500 GeV/c^2 (90% CL)[53].

For top-quark studies *above threshold*, where $t\bar{t}$ events will be produced at about the same rate as $\mu^+\mu^-$ events, the collider can operate in its highest luminosity mode, producing of the order of 10,000 well reconstructed $t\bar{t}$ events for analysis of angular distributions and decay-modes, allowing new precision measurements of parameters of the $\mathcal{SM}$ and opening new windows on its possible breakdown or extension. Examples listed in Table 2 are the measurements of the top anomalous magnetic $(g-2)$ and electric dipole moments, of its decay $(V \pm A)$ structure, of searches for rare decay modes such as $t \rightarrow H^+ b$ and $t \rightarrow \tilde{t}\tilde{\chi}_1^0$, and of the Yukawa coupling. The measurements tend to require higher luminosity and energy and also beam polarization for those involving the analysis of helicity states.

A LEP/SLC-sized detector could do many of these measurements [24, 25, 30]. Hermetic coverage down to $|\cos\theta| < 0.98$ is important for forward-backward measurements of the helicity structure and for detecting rare decays involving the $\tilde{\chi}_1^0$. Good lepton I.D. is essential for studying the leptonic decays of top, for the p_{top} measurement during the threshold scan, for the helicity analyses and for the study of rare decays $t \rightarrow H^+ b$, $H^+ \rightarrow \tau^+ \nu$. The latter reaction also calls for good vertex detection, which is important for the standard $t \rightarrow W^+ b$ decay mode. For the calorimetry/energy-flow measurement, the calibration error must be below 1% to enable an uncertainty in the M_{top} measurement to less than $\pm$500 MeV/c^2.

• QCD

The measurement of the energy dependence of the strong coupling constant is an important measurement of the $\mathcal{SM}$, and requires the machine energy to be varied over a broad range [39]. Other QCD studies include the measurement of the general properties of hadronic final states. Mainly the tracking and calorimetry of the detector should be good but do not have to be excellent for these studies, and the

lower luminosity expected in the early operating phase of the machine is sufficient.

• Two-photon physics

Even at an e^+e^- collider there are useful event rates both from virtual photon collisions and from beamstrahlung collisions with virtual photons. The higher energy and luminosity of the linear collider will significantly enhance the precision physics which is being done at TRISTAN and LEP - particularly studies of heavy flavour production and the determination [38] of the quark and gluon structure of the photon by measurement of hadronic $\gamma\gamma$ events with and without an observed final state electron.

B Topics for e^-e^-, $\gamma\gamma$, and $e^-\gamma$ Collider Programmes

These programmes are in the formation stage, even though much theoretical work has been and is being done [45, 48]. The reason that clear goals which make a solid physics case are still being discussed is that these programmes will follow the 0.5 TeV e^+e^- phase of the machine. The e^-e^-, $\gamma\gamma$, and $e^-\gamma$ reactions encompass $\mathcal{SM}$ and non-$\mathcal{SM}$ physics similar to e^+e^-, and are also complementary to e^+e^- since other Feynman diagrams govern the processes. More emphasis is needed on the importance of the complementary aspects of e^-e^-, $\gamma\gamma$, and $e^-\gamma$ physics, since their exploration will come after the e^+e^- physics has been extracted from the 0.5 TeV running.

B.1 The e^-e^- Collider

This collider does not need a special laser-backscatter system. e^-e^- collisions could be studied in an early phase of the machine with a normal e^+e^- interaction region and detector [48]. The only special requirement would be a second polarized electron source. The luminosity will be a factor of two or three lower than the corresponding e^+e^- luminosity since the beams will blow up rather than pinch.

Examples are

$e^-e^- \to e^-W\nu$: copious production for precision tests of the standard model;
$e^-e^- \to H^{--}$: in case of existence of an extended Higgs sector;
$e^-e^- \to X^{--}$: production of a possible dileptonic boson;
$e^-e^- \to e^-e^-$: anomalous effects in Moller scattering reveal substructure or Z' effects;
$e^-e^- \to W^-W^-$; due to the exchange of a heavy Majorana neutrino.

B.2 The $\gamma\gamma$ Collider

The reaction $\gamma\gamma \rightarrow Higgs$ can give an indirect window to new physics in a similar way that the precision LEP/SLC measurements are sensitive to the top quark and Higgs boson masses. Polarization of incoming laser light and of the electrons can be used to give a narrow energy peak on-resonance.

The most important quantity to be measured is $\Gamma_{\gamma\gamma \rightarrow Higgs}$, which could have an anomalous value without violating present knowledge, and it could be sensitive to loops of undiscovered heavy charged particles. Thus the Higgs couplings and branching ratios test for $\mathcal{SM}$, $\mathcal{MSSM}$, or extended-$\mathcal{SUSY}$ particles. One would measure, for example, $\gamma\gamma \rightarrow$Higgs$\rightarrow b\bar{b}$ or $\gamma\gamma \rightarrow$Higgs$\rightarrow Z^0Z^0$, depending on the value of M_{Higgs} up to 300 GeV/c^2 for the 0.5 TeV phase of the collider [45].

Other important examples are
$\gamma\gamma \rightarrow H^0$or A^0which are possible for some $\mathcal{MSSM}$ scenarios,
$\gamma\gamma \rightarrow \tilde{t}\bar{\tilde{t}}$, which is favored by angular momentum over the equivalent e^+e^- channel,
$\gamma\gamma \rightarrow t\bar{t}$, which has a larger cross section than in e^+e^- production due to the coupling to the charge of the top quark, and
$\gamma\gamma \rightarrow W^+W^-$ and $W^+W^-Z^0$, for which the copious production allows for precision tests of anomalous couplings, complementary to the e^+e^- measurements.

B.3 The $e^-\gamma$ Collider

Interesting processes which this machine is ideal to study include:

Copious production of $e^-\gamma \rightarrow W^-\nu$ provides a complementary measurement of the $WW\gamma$ coupling.

The reaction $e^-\gamma \rightarrow \tilde{e}\tilde{\gamma}$ is likely to provide the lowest observable SUSY particle threshold, possibly with a cross section as large as $\sim$10 fb [50]. Analysis is straightforward with a clear single electron signal and a mass measurement from the Jacobian peak in p_T.

Hundreds of events of the type $e^-\gamma \rightarrow \nu tb$ will be produced with 10 fb^{-1}, providing an excellent laboratory for measuring $|V_{tb}|$.

The process $e^-\gamma \rightarrow e^-$(tagged)+ hadrons will allow the study of the quark structure of the photon to lower x and higher Q^2 than by any other technique [51]. The detector will require a small-angle tagger. Polarized beams will give access to polarized structure functions. Similarly, the process $e^-\gamma \rightarrow$jets or inclusive heavy flavour will allow for the study of the gluon structure of the photon.

B.4 Extension to Energies > 1 TeV

The new particle search channels may need an extension of the energy, but an additional strong motivation will come if there is no light Higgs boson [45].

$\gamma\gamma \rightarrow WWZZ, WWWW$, with > 100 fb^{-1}: a 700 GeV/c^2 Higgs may appear as a broad final state $W_L W_L$ resonance, or enhanced rates may be seen [47]. The strongly interacting electroweak sector could generate a family of narrower$W_L W_L$ resonances at higher mass.

$e^- e^- \rightarrow \nu\nu W^- W^-$ with > 200 fb^{-1}: this experiment would give unique access to $I = 2$ resonant states for production of strong $W_L W_L$ resonances [48].

C Z^0-Peak Running for Physics

One of the primary goals of precision electroweak measurements is to be sensitive to the Higgs boson mass. An e^+e^- linear collider, running at the Z^0-peak with longitudinally polarized beams and with higher luminosity than the SLC, could do excellent measurements in this field since, even if the Higgs has been discovered, it can probe sensitively the internal consistency of the $\mathcal{SM}$. This was first discussed in the JLC report[4].

At present the main limitation on the sensitivity to M_{Higgs} comes from the poor knowledge of M_{top}, but this should improve soon with new measurements from the Tevatron. From the precision on $\sin^2\theta_W$ of ± 0.0003 which should be achieved by LEP and SLC and from the accuracy on M_{top} from Fermilab of ± 5 GeV/c^2, one would be able to set a significant upper bound on the Higgs mass provided its central value is below 150 GeV/c^2, as predicted by $\mathcal{SUSY}$. In that case the upper bound would be $\sim$500 GeV/c^2 at 90% confidence level (CL), which would imply that the Higgs boson should be observed directly at future colliders, and if it is not observed, then something is wrong with the $\mathcal{SM}$. If the M_{Higgs} is lighter, i.e. $\sim$100 GeV/c^2, its mass would be known to $\pm$40-50 GeV/c^2[53].

If the upper bound is inconclusive, for example because of measurement errors or if no light Higgs is found at the e^+e^- linear collider or at LHC, then it would seem urgent to cross-check and sharpen the indirect determinations of the Higgs mass. The linear collider can help in two ways: (1) with the accurate M_{top} measurement to ± 0.5 GeV/c^2 and (2) with a measurement of $\mathcal{A}_{LR}$ which improves on that of SLC. The latter would be possible if the accuracy of the polarization measurement can be improved. Assuming $\delta P/P \leq \pm 0.5\%$, i.e. twice as good as SLD, then with only 100pb^{-1} of data taken at the Z^0-peak, $\sin^2\theta_W$ could be measured to ± 0.0001. Thus a luminosity of $\sim 5 \times 10^{31}$cm^{-2}s^{-1} would suffice. This error on the polarization is easily achievable if e^+ polarization is available[52]. At this level of accuracy there is

a new limitation due to uncertainties on $\alpha(M_Z)$ coming from poor knowledge of the hadronic cross section in e^+e^- below 10 GeV. Assuming that progress in the near future will reduce this uncertainty by a factor of two, then the Z^0-peak running would set an upper bound on the Higgs mass of, for example, 800 GeV/c^2 (90% CL) for a central value of $M_{\phi^0} \simeq 500$ GeV/c^2.

This option would thus open new avenues for attack on the $\mathcal{SM}$ via precision measurements using polarized beams with modest requirements on luminosity. Another example is the measurement of $\sin^2\theta_W$ for different flavors.

If 10^{33}cm^{-2}s^{-1} is available for Z^0-pole running, then experiments become feasible such as measuring CP violation in the b-quark sector [4], or B_s^0 oscillations [54], in case there are still open questions from experiments now in preparation.

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