SSCL-347

Superconducting Super Collider Laboratory

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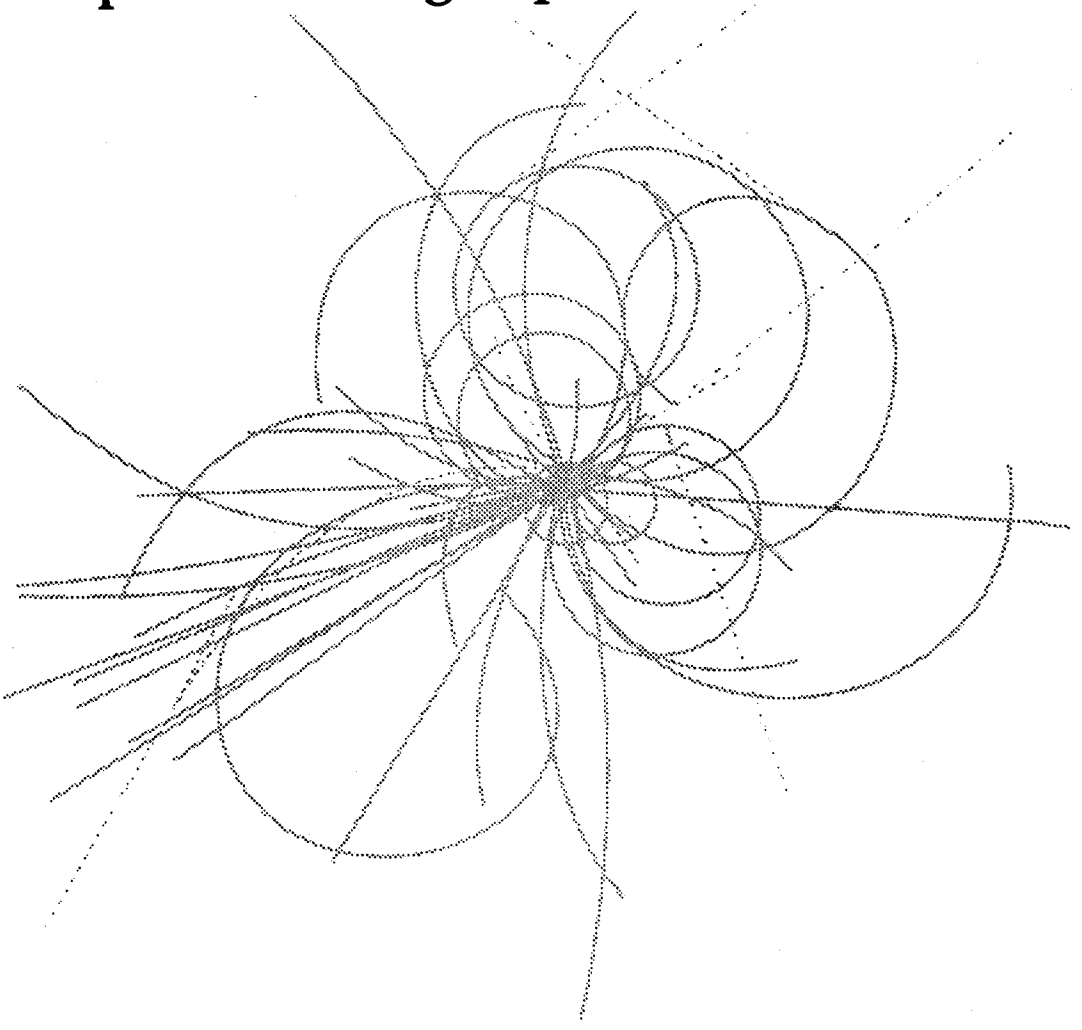

The B Factory, The Superconducting Super Collider, and An e^+e^- Linear Collider: How They Stand Against Each Other

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THE B FACTORY, THE SUPERCONDUCTING SUPER COLLIDER, AND AN e^+e^- LINEAR COLLIDER: HOW THEY STAND AGAINST EACH OTHER*

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1. INTRODUCTION

Many high energy physicists in Japan will be participating in Superconducting Super Collider (SSC) experiments. KEK is planning to build a B factory. Japan Linear Collider (JLC)—an e^+e^- linear collider with $\sqrt{s} = (.5 \sim 1.5)\,\mathrm{TeV}$—is being considered as the future project at KEK. I have been asked to discuss the physics compatabilities and the relative merits of these three projects.

From a physics point of view, nobody can argue against building an accelerator. Looking back at the past 40 years, we note that physics discoveries from new accelerators often far exceeded our original expectations. Such temptations, however, must be balanced against reality:

- Ever larger accelerators become very costly.
- Manpower requirements have become overwhelming.
- With the discovery of particles with masses of order 100 GeV, the energy scale for interesting physics has expanded faster than the energy region that can be covered by accelerators.

In order to make accelerators cost effective, their parameters must be tuned so that there is *guaranteed physics*. By guaranteed physics, I mean that a machine must be capable of observing new phenomena predicted by the most conventional standard model. Discoveries beyond such bottom line expectations should be treated as bonuses and should not be treated as major motivations for building a machine.

I will first discuss the bottom line physics at SSC and at a B factory. I will then go on to discuss the compatability of the two physics. Finally, I will discuss the physics at JLC, and its relationship with that at SSC and at a B factory.

2. THE BOTTOM LINE PHYSICS AT SSC

Candidates for physics beyond the standard model which will be studied at SSC are discussed in a lecture by Quigg[1]. In accordance with our philosophy stated above, I concentrate here on physics predicted by the standard model.

The most conventional standard model of the electroweak interaction requires a Higgs lagrangian

$$L_H = \frac{1}{2}\partial_\mu\phi^\dagger\partial^\mu\phi + \frac{1}{2}\mu^2\phi^\dagger\phi - \frac{\lambda}{4}(\phi^\dagger\phi)^2,$$

where

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^- \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} \omega_1 + i\omega_2 \\ v + H + i\omega_3 \end{pmatrix}.$$

Here, I have decomposed ϕ into ω_1, ω_2, ω_3 and H. The pseudo-Nambu-Goldstone bosons ω_i become the longitudinal components of the gauge bosons and H becomes the physical Higgs particle. In terms of these variables, L_H becomes

$$L_H = \frac{1}{2}\partial_\mu\vec{\omega}\cdot\partial^\mu\vec{\omega} + \frac{1}{2}\partial_\mu H\partial^\mu H - \lambda v^2 H^2 - \lambda v H[\vec{\omega}\cdot\vec{\omega} + H^2] - \frac{1}{2}\lambda[\vec{\omega}\cdot\vec{\omega} + H^2]^2,$$

and the vacuum expectation value $v = \dfrac{2M_W \sin\theta_W}{e} = 250\,\mathrm{GeV}$, where M_W, $\sin\theta_W$, and e, are the W mass, the Weinberg angle, and the electric charge, respectively. First thing to note is that this lagrangian is identical to that of the σ model if we make the following identifications:

$$\vec{\omega} \to \vec{\pi}$$
$$H \to \sigma$$
$$v \to f_\pi.$$

This lagrangian is very rich in dynamics: PCAC, low energy theorems, etc.

The mass and the width of the Higgs boson is given by

$$M_H^2 \sim \lambda v^2$$
$$\Gamma_H \sim G_H M_H^3 \qquad \text{for } M_H \geq 2M_W.$$

If $200\,\mathrm{GeV} \leq M_H \leq (600 \sim 800)\,\mathrm{GeV}$, i.e., $\lambda \leq (3 \sim 5)$, SSC can detect the resonance in the $H \to ZZ \to 2\mu^+ + 2\mu^-$ channel. It is unlikely that the Higgs

will be found if M_H is larger than the above range. If this is so, the electroweak symmetry breaking lagrangian becomes strong coupling, i.e., $\lambda \geq (3 \sim 5)$. Can SSC study the Higgs boson dynamics in the strong coupling limit?

3. HIGH ENERGY GAUGE BOSON SCATTERING

In the Higgs mechanism, the W and Z bosons become massive by "eating" the pseudo-Nambu-Goldstone bosons, ω_1, ω_2, and ω_3. Above, we mentioned that the dynamics of ω_i are governed by the σ model lagrangian. How could this dynamics be studied experimentally? Here, I shall repeat the essential features of the equivalence theorem.[2]

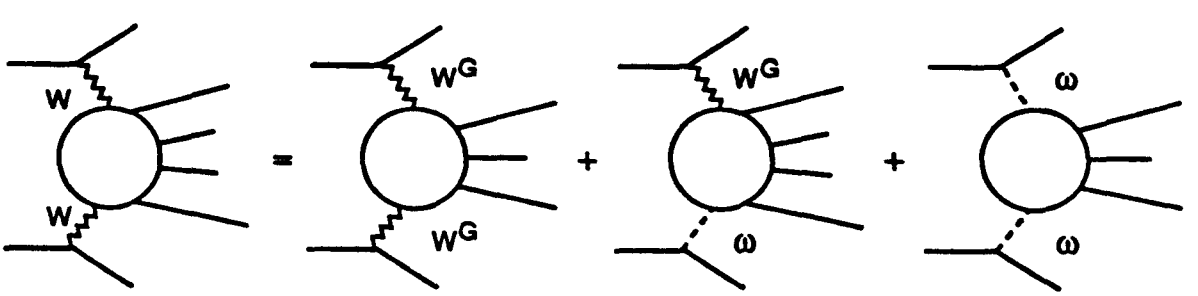
It is well known that, in the spontaneously broken gauge theories, the vector meson propagator is written as [3]

$$-i\,\frac{g_{\alpha\beta} - \dfrac{q_\alpha q_\beta}{M_W^2}}{q^2 - M_W^2} = -i\,\frac{g_{\alpha\beta} - \dfrac{q_\alpha q_\beta}{q^2}}{q^2 - M_W^2} + i\,\frac{1}{M_W^2}\,\frac{q_\alpha q_\beta}{q^2}$$

which I denote as

$$\Delta^W_{\alpha\beta} = \Delta^G_{\alpha\beta} + \Delta^\omega q^\alpha q^\beta .$$

The first term on the right side is the propagator for the transversely polarized gauge boson. The second term on the right side can be interpreted as the contribution from the pseudo-Nambu-Goldstone bosons, ω_i, which become the longitudinal component of the W. A relevant diagram for WW scattering is given by



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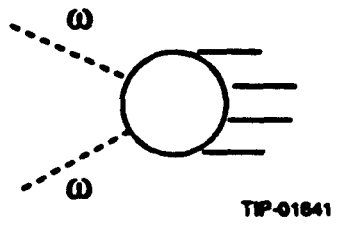
Note that W^G, the transverse W, couples to matter with the gauge coupling constant g, and ω couples to ω and H with the coupling λ. Thus when $\lambda \gg g$, the WW scattering may be dominated by the $\omega\omega$ scattering components. This contribution is given by

$$= \frac{q_1^\alpha}{M_W} \frac{q_2^\beta}{M_W} T_{\alpha\beta}$$

$$\sim \epsilon_{1L}^\alpha \epsilon_{2L}^\beta T_{\alpha\beta}$$

in the high energy region, where M_W is negligible, $\frac{q_1^\alpha}{M_W}$ can be identified as ϵ_{1L}^α. The right side is precisely the scattering amplitude for the longitudinally polarized W's. Their WW and WZ scatterings at high energy can be predicted from those of Nambu-Goldstone bosons ω_i depicted below.



Now the phase shifts for WW and WZ scatterings are predictable from the results of the sigma model[4] and perhaps these predictions can be checked. If this is the case, the presence of spin 1, isospin 1 WW resonance which corresponds to the ρ meson in the $\pi\pi$ resonance should be most prominent. A crucial question here is to understand to what extent the σ model predicts the existence of the ρ resonance. We point out that the Páde approximation based on the power series expansion (in λ) of the $\pi\pi$ scattering amplitudes to one loop gives the prediction[5]

$$m_\rho \sim 750\,\mathrm{MeV}$$

$$\Gamma_\rho \sim 35\,\mathrm{MeV}$$

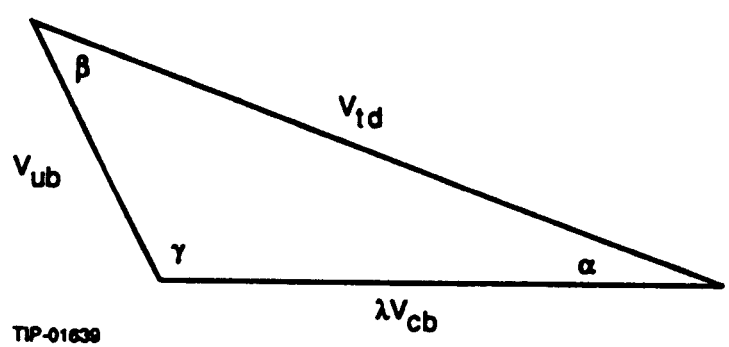
The ρ mass is in agreement with experiment while the width is not. Perhaps this can be understood by the fact that the one loop approximation to the $\pi\pi$ scat-

tering is much more reliable for its real part than for its absorptive part. This is presently under investigation.[6]

4. PHYSICS AT A B FACTORY

We are not the first to ask, "Why do we exist?". Within the context of particle physics, we know that a partial answer to this question has to do with the nonconservation of baryon number and CP asymmetry. In a specific model, this requires that CP is violated in some grand unified theory with some baryon number changing interaction. It is then natural to assume that this CP violation, somehow, manifests itself in the observed CP-violating $K_L \to 2\pi$ decay. Thus, by studying the low energy effect of CP violation in B and K decays, we may probe the physics at the GUT scale.

The physics of B decays based on the standard model of electroweak interaction with mixing of three quark families by the KM matrix can be summarized by a unitarity triangle:



All six quantities are accessible to experiments, at least in principle:

V_{cb}	B meson life time
V_{ub}	$\frac{\Gamma(b\to u)}{\Gamma(b\to c)}$
V_{td}	$\frac{x_t}{x_d}$
α	CP asym in $B \to \psi K_S$ channel
β	CP asym in $B \to \pi\pi$ channel
γ	CP asym in B_s decay

In order to perform an accurate test of the standard model, it is necessary to perform accurate measurements of at least 3 of these quantities. This possibility has been studied at previous workshops.[7]

5. THE SSC PHYSICS AND THE B FACTORY PHYSICS

It is well known that the KM matrix arises from the complex Yukawa coupling of quarks to a doublet of Higgs field:

$$L_{\text{Yukawa}} = \sum_{ij} g^d_{ij} \begin{pmatrix} \overline{U_i} \\ D_i \end{pmatrix}_L \begin{pmatrix} \phi^+ \\ \phi^o \end{pmatrix} D_{jR} + g^u_{ij} \begin{pmatrix} \overline{U_i} \\ D_i \end{pmatrix}_L \begin{pmatrix} -\phi^{o*} \\ \phi^- \end{pmatrix} U_{jR}.$$

Experimental determination of the KM matrix may shed some light on a fundamental theory which generates such Yukawa couplings. More importantly, to get at the fundamental theory which leads to the standard model, we must know if any other source of CP violation is needed.

The connection between SSC and B factory physics can be seen as follows: Write

$$L_{EW} = L_{\text{gauge}} + L_{\text{Higgs}} + L_{\text{Yukawa}}.$$

L_{gauge} is the part of the electroweak lagrangian which describes the interaction of gauge bosons. Experiments at various e^+e^- colliders, experiments with neutrino beams, and atomic parity violation experiments have all been in total agreement with the predictions of L_{gauge}.

Less known parts of L_{EW} are L_{Higgs} and L_{Yukawa}. We have argued above that experiments at SSC and at a B factory will yield information on L_{Higgs} and L_{Yukawa}, respectively, thus completing the study of L_{EW}. It should be stressed that these two parts of L_{EW} are more arbitrary than L_{gauge}—giving us some hope of observing a deviation from the standard model predictions.

Physics of SSC and B factory, the study of L_{Higgs} and L_{Yukawa}, respectively, are:

(*a*) Comparable in the following sense:

(*i*) Both L_{Higgs} and L_{Yukawa} have not been tested.

(*ii*) Both are necessary stepping stones towards the physics beyond the standard model.

(*b*) Dependent on each other in the sense that if one is shown to be inconsistent, then the other should also be inconsistent, or at least incomplete.

6. AN e^+e^- LINEAR COLLIDER AT $\sqrt{s} = 1\,\text{TeV}$, JLC

If $M_H \sim 100\,\text{GeV}$, the Higgs bosons will be found at Lep I or Lep II. JLC is sensitive to $M_H \leq 600\,\text{GeV}$ and SSC is sensitive to $200\,\text{GeV} \leq M_H \leq 800\,\text{GeV}$. Unless JLC is built before SSC[8], the window for the Higgs boson discovery ($100\,\text{GeV} \leq M_H \leq 200\,\text{GeV}$) is rather small. This is not to say the JLC should not be built. While SSC is a discovery machine, a detailed study of the Higgs boson—decay properties, for example—is rather difficult. A machine like JLC should be very good for this type of study. But it is difficult to choose the beam energy without any prior information on M_H. Thus the energy of JLC should be fixed in accordance with the findings at SSC.

At this time an R&D program for JLC which covers all energies up to $\sqrt{s} \sim 10\,\text{TeV}$ is very important.

If the couplings in L_{Higgs} are strong and M_H and Γ_H are too large to be observed at SSC, then a detailed study of WW and WZ scatterings is needed to study L_{Higgs}. Can this be done at JLC? A study along this line, including that of background processes such as $\gamma W \to ZW$, concludes that $\sqrt{s}$ must be at least $3\,\text{TeV}$ with $L \sim 10^{34}\,\text{cm}^{-2}\text{sec}^{-1}$, in order for it to be sensitive to the strong WW scattering.

7. CONCLUSION

In view of the expanding energy region in which we expect relevant physics, 10^2 GeV $\sim 10^{15}$ GeV, choosing the parameters of accelerators is now much more challenging than in the past. It is necessary to tune the parameters of accelerators so that the physics output per cost is maximized. One guideline in accomplishing this task is to make sure that there are well-defined, guaranteed physics results before we set out to build an accelerator.

SSC and a B factory propose to study L_{Higgs} and L_{Yukawa}, respectively. They have complementary objectives which complete the study of the standard model. In this sense there are guaranteed physics at these accelerators. Needless to say, we hope to be rewarded by discoveries which pave the way toward the fundamental theory for which the standard model is a low-energy manifestation.

The e^+e^- linear colliders are very powerful in studying detailed properties of the Higgs and the gauge boson scatterings. These are not easily accessible at SSC. In this sense, the capability of JLC complements that of SSC. It is, however, too costly to cover the entire energy region accessible to SSC. For this reason, it is useful to fix the JLC energy in accordance with the SSC findings—where the physics is!

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