PHYSICS WITH LOW-ENERGY e^+e^- AND e^-e^- COLLISIONS AT TAU–CHARM FACTORY*

K. K. GAN

Stanford Linear Accelerator Center
Stanford University, Stanford, CA 94309

ABSTRACT

The physics opportunities in e^+e^- collisions with $\sqrt{s} \simeq$ 1–2 GeV and e^-e^- collisions with $\sqrt{s} \sim 5$ GeV at Tau–Charm Factory are being explored. The low-energy e^+e^- option allows precise measurements of e^+e^- cross sections into π's and η's and hence stringent tests of the conserved-vector-current (CVC) hypothesis in τ decays. Precise measurement of the total hadronic cross section also permits a more precise calculation of the muon anomalous magnetic moment (g–2). The e^-e^- option provides an opportunity for a sensitive search for lepton-number violating processes $e^-e^- \to \mu^-\mu^-$, $\tau^-\tau^-$, $\mu^-\tau^-$ .... The e^-e^- collider also provides an ideal laboratory for two-photon physics with no one-photon background and the direct measurement of the two-photon background in one-photon physics!

1. INTRODUCTION

The Tau–Charm Factory is a high-luminosity e^+e^- collider with two rings. The collider is optimized at center-of-mass energy of $\sqrt{s} \sim 5$ GeV. Collisions at much lower energy, $\sqrt{s} \simeq$ 1–2 GeV, will result in substantial loss of luminosity. However, since the cross section at this energy range is enormous, the event rate is still very high. The physics opportunities with this low-energy collider will be discussed in Section 2. The two-ring

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facility also permits e^-e^- collisions, and hence, the search for lepton-number violating processes and the study of two-photon physics. These physics opportunities will be discussed in Section 3. The conclusions are given in Section 4.

2. PHYSICS WITH LOW-ENERGY e^+e^- COLLISIONS

A. Luminosity

The luminosity of Tau–Charm Factory is optimized at $\sqrt{s} \sim 5$ GeV with s dependence. The design luminosity is $\mathcal{L} \sim 10^{33}$ cm^{-2} s^{-1}. Therefore, at $\sqrt{s} \sim 1$ GeV, the luminosity is $\sim 4 \times 10^{31}$ cm^{-2} s^{-1}, and at $\sqrt{s} \sim 2$ GeV, the luminosity is $\sim 16 \times 10^{31}$ cm^{-2} s^{-1}. Since this $\mathcal{L} \propto s$ extrapolation to very low energy may not be very realistic, I will assume an attainable luminosity of 1×10^{31} cm^{-2} s^{-1} in the following calculation of event rate. I also will assume that we scan between 1 and 2 GeV at 10 MeV step for 100 days with 16 hours per day of data taking, while allowing 8 hours for changing beam energy, tuning and other detector/collider down time. This corresponds to 6×10^4 s per day or 600 events per scan point for a cross section of 1 nb. This event rate will be used in the following section for estimating the data sample for various processes.

B. Test of Conserved-Vector-Current Hypothesis in τ Decays

The conserved-vector-current hypothesis[1] (CVC) related the strength of the charged-vector-current coupling of the τ into a hadronic final state with that of the electromagnetic (neutral vector) current to the corresponding hadronic final state in e^+e^- annihilation. All the hadronic decays of the τ will be measured with high precision at Tau–Charm Factory and comparison with the CVC predictions will be limited by the uncertainties in the e^+e^- hadronic cross sections. For example, the branching ratio[2] for $\tau^- \to \pi^-\eta\pi^0\nu_\tau$ is only known to 15%, $B(\tau^- \to \pi^-\eta\pi^0\nu_\tau) = (0.13 \pm 0.02)$.

The e^+e^- cross section in the $\sqrt{s} \sim$ 1–2 GeV region is large, and can be measured with good precision for a luminosity of $\mathcal{L} \sim 1 \times 10^{31}$ cm^{-2} s^{-1}. For example, Fig. 1 shows the cross section of $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ from various experiments. The data exhibits some structures with some disagreement between experiments. We can expect to accumulate thousands of events in a day per data point. This will allow the precise calculation of the branching ratio for the τ decay. With the high statistics in both τ and e^+e^- data, a detailed comparison of the shape of the 4π mass spectrum in the τ decay with the expectation will permit a stringent test of CVC as a function of q^2 and the search for any anomalous current. The data for the process $e^+e^- \to \pi^+\pi^-$ is also sparse for the high q^2 region. More precise measurement of the cross section in this region will be useful.[6] Figure 2 shows the cross section for $e^+e^- \to \eta\pi^+\pi^-$. The data is also sparse. We can expect hundreds of events per data point with the Tau–Charm Factory.

The energy of the photons in the e^+e^- hadronic events is similar to that from τ decay and the detector for the Tau–Charm Factory represents the best neutral detector at this energy. Moreover, unlike the case in τ decay with missing neutrino, energy and momentum conservation allows additional constraints on event reconstruction and better background rejection.

C. Muon Anomalous Magnetic Moment

The muon anomalous magnetic moment has played a central role in establishing the validity of quantum electrodynamics (QED). It also has been used to constrain speculative theories beyond the Standard Model. The most precise measurement[9] of the magnetic moment is:

$$a_\mu^{exp} = 11\ 659\ 240\ (85) \times 10^{-10} \quad ,$$

where the numeral enclosed in parenthesis represents the uncertainty in the final digits. This is in good agreement with the theoretical prediction,[10]

$$a_\mu^{th} = 11\ 659\ 203\ (20) \times 10^{-10} \quad .$$

The theoretical uncertainty is now much smaller than the experimental error. There is an experiment[11] at Brookhaven National Laboratory to measure a_μ to an accuracy of $\pm 4 \times 10^{-10}$. Therefore, there is a great need to calculate a_μ to better precision. The dominant source of theoretical error is the uncertainty in calculating the hadronic contribution,

$$a_\mu^{had} = 703\ (19) \times 10^{-10} \quad .$$

Most of the uncertainty is in the ρ and ω region in $e^+e^- \to \pi^+\pi^-$. There is a plan to scan the region up to $\sqrt{s} \sim 1$ GeV with greater precision at VEPP II collider.[12] The contribution in the $\sqrt{s} \simeq$ 1–2 GeV region is:

$$a_\mu^{had} \simeq 60\ (4) \times 10^{-10} \quad .$$

Therefore, the uncertainty is comparable with the expected experimental precision. A more precise measurement of the hadronic cross section in this region will facilitate the testing of Standard Model in a_μ. Note that the uncertainty in the $\sqrt{s} \simeq$ 2–3 GeV region is also comparable. Some scanning in this region is also highly desirable.

3. PHYSICS WITH e^-e^- COLLISIONS

A. e^-e^- Collider

The Tau–Charm Factory with separate rings for electrons and positrons can be converted into an e^-e^- collider without much difficulty. It is important that we do not exclude the e^-e^- option in the collider design. As an e^-e^- collider, electrons will be injected into both rings with the same linac. At the switch yard, the positron bending magnet should have the capacity to bend electrons into the positron linac for transporting into the positron ring. Beyond the switch yard, the polarity of the magnets in the positron linac and ring need to be reversed. There is a concern with ion trapping problem in the electron ring. If this turns out to be a problem, the same ion cleaning device can be installed in the positron ring; the design of the ring should not exclude this possibility. At the collision point, new separators may be required, depending on the beam crossing angle and the type of separators used. In the case of a finite (crab) crossing angle, no new hardware is required. In the case of a zero crossing angle, r.f. separators will be compatible with the e^-e^- option but not with electrostatic separators. No new detector is contemplated; the detector designed for e^+e^- collisions is well suited for e^-e^- physics.

B. Search for Lepton-Number Violating Processes

The search for a lepton-number violating process has long been a tradition of particle physics. In recent years, the immense interest in models beyond the Standard Model, such as compositeness, technicolor, lepton-quarks, and new horizontal gauge bosons, has intensified interest in the search.[13] The process $e^-e^- \to \mu^-\mu^-$ was searched for[14] 20 years ago using the Princeton–Stanford electron storage ring at $\sqrt{s} = 1.05$ GeV. The Tau–Charm Factory provides an unique opportunity for e^-e^- collisions with high luminosity. The much higher collision energy also increases the number of channels accessible:

$$\begin{aligned} e^-e^- \to\ & \mu^-\mu^- \\ & e^-\mu^- \\ & \tau^-\tau^- \\ & \mu^-\tau^- \\ & e^-\tau^- \quad . \end{aligned}$$

Examples of the production mechanism are: an exotic gauge-boson Z' exchange [Fig. 3(a)]; a doubly charged Higgs exchange [Fig. 3(b)]; or a constituent exchange, as in the composite model [Fig. 3(c)]. The interaction can be characterized by an effective four-fermion point interaction of the form:

$$\mathcal{L} \ = \ \frac{G}{\sqrt{2}}\, \overline{u}_\mu\, \gamma_\alpha\, (1-\gamma_5)\, u_e\, \overline{u}_\mu\, \gamma^\alpha\, (1-\gamma_5)\, u_e \quad ,$$

where G is the interaction coupling strength, assuming a $V{-}A$ Lorentz structure. For a 10^7 s year running at $\sqrt{s} \sim 5$ GeV with a luminosity of $\mathcal{L} \sim 10^{33}$ cm^{-2} s^{-1}, the sensitivity is:

$$G \ \sim \ 10^{-2}\, G_F \quad ,$$

where G_F is the Fermi coupling constant. This corresponds to probing a mass scale of ~ 1 TeV/c^2, assuming weak coupling. The sensitivity can be compared with the limits from other experiments under certain assumptions. For example, in the case of a Z' exchange, the sensitivity on $G_{e\mu}$ and $G_{e\tau}$ is an order-of-magnitude better than those inferred from a study[15] of the reactions $e^+e^- \to \mu^+\mu^-$ and $\tau^+\tau^-$ (see Fig. 4). Similar improvement of sensitivity on G_{ee} over the limit[16] from $e^+e^- \to e^+e^-$ is also expected, if Z' has diagonal coupling. However, in this case, the sensitivity on the product of ee and $e\mu$ couplings is much less than that from the search[17] for the exotic decay $\mu^- \to e^-e^+e^-$,

$$\left(G_{ee}\, G_{e\mu}\right)^{1/2} \;<\; 1 \times 10^{-6}\, G_F \quad ,$$

at the 90% confidence level. Similarly, if Z' also couples to quarks, K decays such as $K_L^0 \to e^+\mu^-$ and $K^+ \to \pi^+ e^+ \mu^-$ have much greater sensitivity.[18] In any case, e^-e^- collider permits the direct probing of $G_{e\mu}$ and $G_{e\tau}$, rather than the product of coupling. All the limits discussed above, except the K decays, are also valid if an H^{--} is exchanged. However, if the H^{--} has only diagonal couplings, then only the Bhabha scattering limit is relevant and there is a loose limit[19] from muonium to antimuonium conversion,

$$\left(G_{ee}\, G_{\mu\mu}\right)^{1/2} \;<\; 0.88\, G_F \quad ,$$

at the 90% confidence level.

In summary, the multiple final states in e^-e^- collider permits the probing of the diagonal and off-diagonal couplings of new interactions in the lepton sector not accessible in the current experiments.

C. Two-Photon Physics

The e^-e^- collider has the added bonus of producing $\gamma\gamma$ interactions without one-photon background such as $e^+e^- \to \tau^+\tau^-$. With the high luminosity, this is an ideal laboratory for two-photon physics. This also permits the measurement of two-photon background to one-photon physics without relying on complicated Monte Carlo calculations. This is particularly useful in any search for exotic or highly suppressed decays. In fact, beam-gas background, which is difficult to estimate accurately, can also be measured from e^-e^- collisions.

4. CONCLUSIONS

After several years of e^+e^- collisions at Tau–Charm Factory with $\sqrt{s} \simeq$ 3–5 GeV, a year of scanning between 1–2 GeV will complement the high energy program and lead to a better understanding of the τ lepton and the muon anomalous magnetic moment. A year of e^-e^- program will permit the probe of new interactions in the lepton sector not accessible in the current experiments. The e^-e^- option can be accommodated in the machine design without much difficulty.

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FIGURE CAPTIONS

Fig. 1. Cross section for $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$ from Novosibirsk[3] ($*$), Frascati[4] ($\bullet$), and Orsay[5] ($\triangle$) as a function of center-of-mass energy.

Fig. 2. Cross section for $e^+e^- \rightarrow \eta\pi^+\pi^-$ from Novosibirsk[7] ($\square$) and DCI[2,8] ($\triangle$ and $\bullet$) as a function of center-of-mass energy.

Fig. 3. Examples of the production mechanism for $e^-e^- \rightarrow \mu^-\mu^-$: (a) an exotic gauge-boson Z' exchange; (b) a doubly charged Higgs exchange; (c) a constituent exchange.

Fig. 4. Limits on the couplings $G_{e\mu}$ and $G_{e\tau}$, assuming a Z' exchange. The solid lines are the current limits[15] and the dashed lines are the expected sensitivity at Tau–Charm Factory.

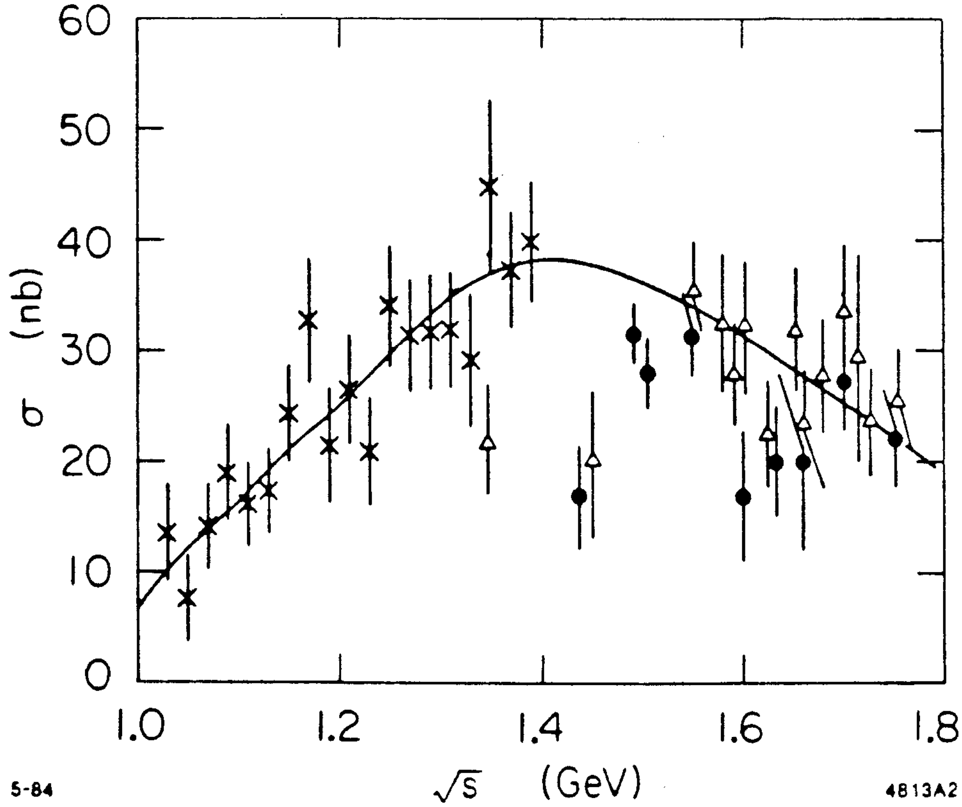


Fig. 1

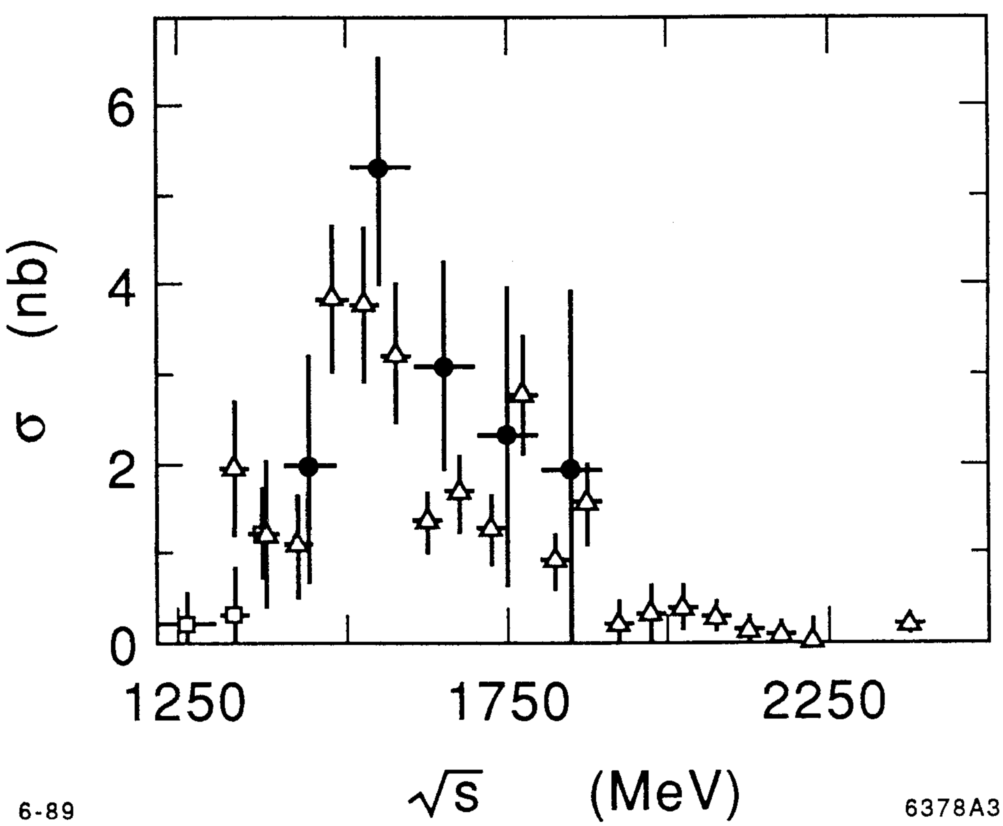


Fig. 2

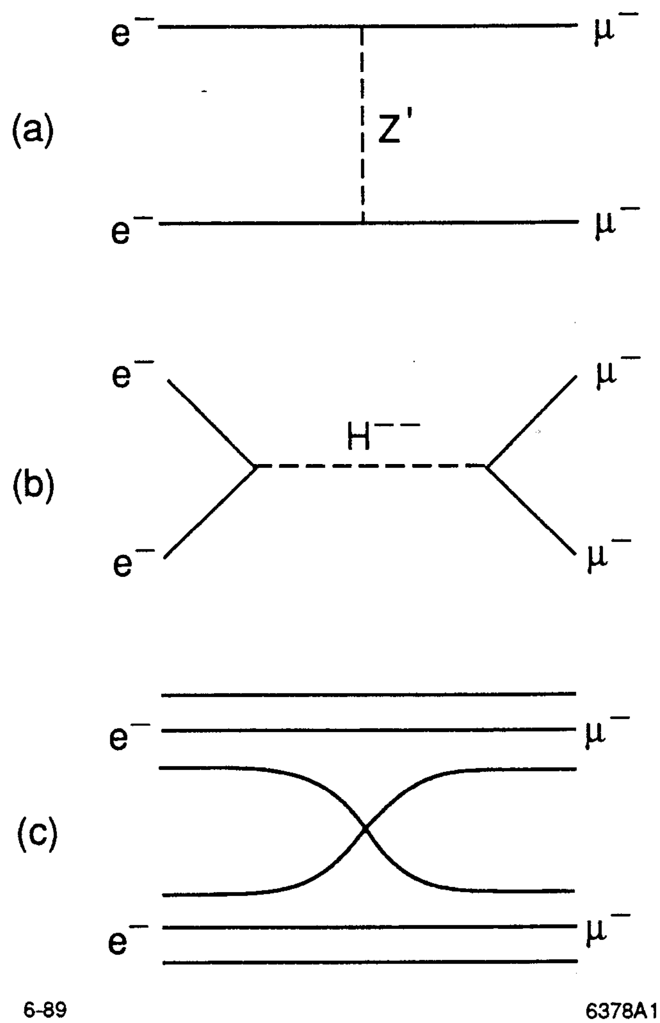
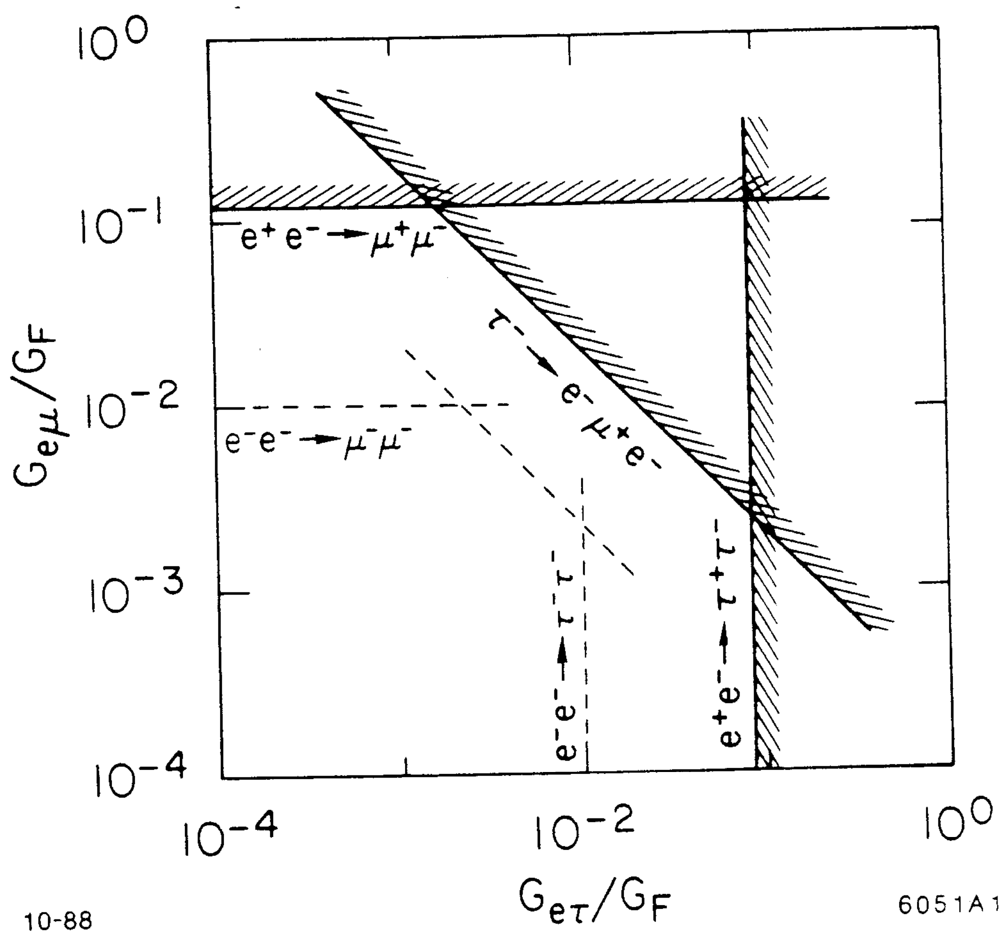


Fig. 3



10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$G_{e\mu}/G_F$
$e^+e^- \to \mu^+\mu^-$
$e^-e^- \to \mu^-\mu^-$
$\tau^- \to e^-\mu^+e^-$
$e^-e^- \to \tau^-\tau^-$
$e^+e^- \to \tau^+\tau^-$
10^{-4}
10^{-2}
10^0
$G_{e\tau}/G_F$
10-88
6051A1

Fig. 4