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**The Possibility of Using a Large Heavy-Ion Collider for Measuring the
Electromagnetic Properties of the Tau Lepton ***

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Abstract

We study the potential of a large heavy-ion collider for the measurement of the electromagnetic properties of the tau lepton. Measuring the anomalous magnetic and the electric dipole moments of the tau at $q^2 \sim 0$ with a precision of $\sim 4 \times 10^{-5}$ and $\sim 4 \times 10^{-3}$, respectively, at the LHC and/or SSC should be no problem. Whereas the precision at RHIC should be a few per cent, comparable to present limits and to the expected precision at LEP.

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A large heavy-ion collider is an interesting facility not only for providing a new physical environment of quark-gluon plasma but for standard, few particle (elementary) physics [1]. At this respect a relativistic heavy-ion is a huge source of photons, allowing to use a large heavy-ion collider as a $\gamma\gamma$ collider [2-5]. As a matter of fact a large heavy-ion collider was proposed as a place to look for an intermediate mass Higgs, $m_Z < m_H < 2m_W$, although this appears to be difficult [2, 3, 6]. It has also been pointed out that it can be used to measure the γWW and $\gamma\gamma WW$ couplings [7]. In both cases the total invariant mass of the final state is large. In contrast the photons supplied by a large heavy-ion collider are almost real and not very energetic. This means that this abundant source of $\gamma\gamma$ collisions is efficient for producing states with small rapidities and low invariant masses, in particular for producing tau pairs, $^{206}Pb^{206}Pb \rightarrow ^{206}Pb^{206}Pb\gamma\gamma \rightarrow ^{206}Pb^{206}Pb\tau\bar{\tau}$. This makes a large heavy-ion collider an interesting place to study the electromagnetic properties of the tau lepton. In fact, it may be competitive for this particular purpose with a *bona fide* e^+e^- tau factory [8]. The expected number of events is typically the same. The advantages of an e^+e^- tau factory are that the events are very clean and its center of mass energy is well-known. On the contrary the longitudinal momentum of the $\gamma\gamma$ collision can not be reconstructed for a $\tau\bar{\tau}$ pair at a large heavy-ion collider. However, *being the photons almost real LHC and/or SSC may be the best places to measure the electromagnetic properties of the tau lepton at $q^2 \sim 0$* [9]. In an e^+e^- machine the exchanged photon has the energy of the $\tau\bar{\tau}$ pair. One can also look at real photon emission, for instance at the Z^0 peak [10], but then the cross section is smaller.

In this letter we estimate the precision with which the anomalous magnetic (F_2) and the electric dipole (F_3) moments of the tau lepton could be eventually measured at a large heavy-ion collider. The electromagnetic tau vertex can be written (in an obvious notation) [11]

$$-ie\bar{u}(p')(\gamma^\mu + iF_2(q^2)\sigma^{\mu\nu}\frac{q_\nu}{2m_\tau} + F_3(q^2)\gamma^5\sigma^{\mu\nu}\frac{q_\nu}{2m_\tau})u(p)\epsilon_\mu(q). \quad (1)$$

Using the decay $Z^0 \rightarrow \tau\bar{\tau}\gamma$ and $10^5 Z^0$ the bound $|F_{2,3}(0)| < 0.11$ has been obtained at LEP[10]. With a 50 times larger statistics the bound would be comparable to the 1σ bound for F_2 , 0.014, quoted in Ref. [12]. (In this case, however, the linear dependence on F_2 should be included in the fit for $\frac{m_\tau}{M_Z}$ is of the same order as the limit on F_2 .) A similar bound has been derived for F_3 from the angular distribution of $e^+e^- \rightarrow \tau^+\tau^-$ at PETRA, $|F_3((35GeV)^2)| < 0.025$ [13]. These bounds should be

improved at a large heavy-ion collider. In fact, the point-like character of the tau lepton could be tested. In particular, the lowest order (electromagnetic) radiative contribution to the anomalous magnetic moment, $\frac{\alpha}{2\pi} = 0.00116$, could be established at the per cent level. On the other hand the upper bound on the electric dipole moment could be lowered to a few per mile. For these estimates we assume that all the tau pairs are detected, although realistic efficiencies should not be better than 10% as we argue below. In this case the precision is overestimated by a factor ~ 3 .

The calculation of the process $^{206}\text{Pb}^{206}\text{Pb} \rightarrow ^{206}\text{Pb}^{206}\text{Pb}\gamma\gamma \rightarrow ^{206}\text{Pb}^{206}\text{Pb}\tau\bar{\tau}$ requires the convolution of the two-photon luminosity with the two-photon tau-pair production. For the effective $\gamma\gamma$ differential luminosity we use the exact expression advocated by Cahn and Jackson in Ref. [4], which should apply to tau production. In the collisions we are interested the nuclei pass by each other without disruption. This case has been discussed by several groups [2-5], varying their results typically by a factor ~ 2 . Our estimates should not have a better accuracy. Whereas the $\gamma\gamma \rightarrow \tau\bar{\tau}$ cross section for the electromagnetic tau coupling given above can be easily calculated [14].

We present numerical results for LHC and SSC $^{206}\text{Pb}^{206}\text{Pb}$ colliders, assuming an energy per nucleon of 3.4 and 8.0 TeV and a luminosity of 10^{28} and $10^{27} \text{ cm}^{-2} \text{ s}^{-1}$, respectively. We will comment on RHIC, as well as on the case of a larger SSC luminosity. The total $\tau\bar{\tau}$ cross section for vanishing $F_{2,3}$ is $\sim 1(1.5) \text{ mb}$ at LHC (SSC). This stands for $\sim 10^8(1.5 \times 10^7)$ events per year, assuming they run $\frac{1}{3}$ of the time. In Fig. 1a (b) we plot the χ^2 distribution,

$$\chi^2 = \sum_i \frac{(N_i(F_{2(3)}) - N_i(0))^2}{N_i(F_{2(3)})}, \quad (2)$$

as a function of $F_{2(3)}$ for $F_{3(2)} = 0$. For vanishing $F_{2,3}$, $\chi^2 = 0$. N_i is the number of events per year in the bin i . We plot two curves for each case and collider, the lower (upper) one corresponds to the total cross section σ (differential cross section $\frac{d\sigma}{d\cos\theta}$, where θ is the $\gamma\tau$ angle in the $\tau\bar{\tau}$ center of mass system). For the total cross section there is only one bin, $i = 1$. Whereas for the differential cross section we have divided the $\cos\theta$ interval into ten bins, $i = 1, \dots, 10$. Both curves are close (indistinguishable for F_2), meaning that unless the experimental efficiency strongly depends on $\cos\theta$ both distributions give similar bounds. An estimate of the precision with which $F_{2,3}$

could be measured is given by the 1σ value,

$$|F_2| = 4 \times 10^{-5} (10^{-4}) \quad (3)$$

and

$$|F_3| = 4 \times 10^{-3} (7 \times 10^{-3}) \quad (4)$$

at LHC (SSC). Obviously the origin of a new contribution can not be established by looking to the total cross section. Besides, it may be difficult to normalize it. Clearly the differential cross section has more information. A discussion of the different observables which could be measured in this process [15], as well as a detailed estimate (with a proper Monte-Carlo generator and realistic cuts) will be presented elsewhere.

It must be noted that the precision for F_2 is higher than that for F_3 because the cross section depends linearly on F_2 but quadratically on F_3 . This is so for whereas the anomalous magnetic moment interferes with the minimal coupling, the electric dipole moment does not. This makes no difference for large $F_{2,3}$ values but it does for small ones.

The limits for SSC but with a 10 times larger luminosity are practically the same as those for LHC, because the SSC cross section is only 1.5 times larger than for LHC. For RHIC the total cross section is more than 3 orders of magnitude smaller than for LHC or SSC. Hence, for the same luminosity as for LHC or SSC the expected limits at RHIC are comparable to present limits and to the expected limits at LEP (discussed above). In fact, the limit on F_3 should be slightly worse but the limit on F_2 could be better for the F_2 linear term is not suppressed by the inverse power of the Z^0 or any other large mass.

Up to now we have assumed that *establishing that a $\gamma\gamma$ collision has taken place without disruption of the two heavy ions and a $\tau\bar{\tau}$ pair has been produced should be no problem*. However, due to the τ branching ratios and to the necessary cuts, the efficiency for tau detection should not be larger than 10%. *The $\gamma\gamma$ collisions we are dealing with are central, besides the tau leptons are mainly produced at rest*. As most of the $\gamma\gamma$ collisions satisfy $m_{\tau\bar{\tau}} \sim 2m_\tau$, the singular behaviour of the $\gamma\gamma \rightarrow \tau\bar{\tau}$ cross section in the forward direction in the limit $\frac{m_\tau}{m_{\tau\bar{\tau}}} \rightarrow 0$ does not manifest [11]. This is shown in Figs. 2 and 3. In Fig. 2a we plot the rapidity distribution of the $^{206}\text{Pb}^{206}\text{Pb} \rightarrow ^{206}\text{Pb}^{206}\text{Pb}\gamma\gamma \rightarrow ^{206}\text{Pb}^{206}\text{Pb}\tau\bar{\tau}$ collisions and in Fig. 2b we plot the

same distribution but for the most probable $\tau\bar{\tau}$ invariant mass, $W = m_{\tau\bar{\tau}} \sim 2m_\tau$. Both distributions exhibit the central character of the two-photon collisions. Whereas in Fig. 3a we plot the squared invariant mass (W^2) distribution and in Fig. 3b we plot the same distribution but for the most probable rapidity, 0. These show that the tau production is mainly at threshold. As a consequence a large part of the events will reach the detector. The (unavoidable) drawback of the production of tau leptons at rest is the small transverse momenta, p_t , of the tau decay products, on which necessarily we have to trigger. The p_t of the final particles will be typically $\frac{1}{3}$ or $\frac{1}{2}$ the τ mass. Assuming that *to trigger on these particles should be no problem*, the necessary cuts should reduce the number of events by a factor ~ 2 . On the other hand, as the tau decays inside the detector, at least a factor ~ 5 should be paid to take into account the τ branching ratios [16]. For instance, one could trigger on a charged lepton, e or μ , plus a ρ meson, plus missing p_t . The branching ratio for this channel is 16%. A cleaner channel with a branching ratio of 6% would be a couple of different charged leptons, e and μ , plus missing p_t . If we allow a 10% efficiency for tau detection, the 1σ values for the anomalous magnetic and electric dipole moments at LHC (SSC) are

$$|F_2| = 10^{-4}(3 \times 10^{-4}) \quad (5)$$

and

$$|F_3| = 8 \times 10^{-3}(10^{-2}), \quad (6)$$

respectively.

Note Added: When we were writing this letter we became aware of Ref. [17]. There it is pointed out that the abundant Drell-Yan production of lepton pairs in a large heavy-ion collider can be used to bound the electromagnetic couplings of known leptons to new excited fermions. In this case the dependence of the cross section on the new couplings is at least quadratic. Other contributions from new Physics are also considered

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Fig. 1

Fig. 2

Fig. 3