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Remarks Concerning $B^0\bar{B}^0$ Mixing and Single Quark Decays in Toponium*

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ABSTRACT

We discuss the possibility of measuring particle-antiparticle mixing using toponium bound states where the top quark t (or $\bar{t}$) decays weakly. It is suggested to detect $B^0 - \bar{B}^0$ mixing via events having three leptons of the same charge in the final state. Such a signature could lead to samples with a very low background. Estimations are given for an e^+e^- experiment of 200 pb^{-1} assuming that the toponium has a mass in the $70 - 110$ GeV/c^2 range.

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1 - Introduction

Here we will discuss the possibilities of studying particle-antiparticle mixing by means of toponium where one of the bound quarks decays weakly (the so called single quark decay or SQD). We consider the case of toponium formed as an S-channel resonance in e^+e^- interactions and where mixing is measured by means of like sign leptons in the final state (e or μ, denoted throughout by l). In conventional approaches the $T^0 - \bar{T}^0$ system is not expected to manifest a large mixing[1] which could therefore be hardly detectable in the decay of toponium as well (See below). However we will see that the single quark decay phenomenon in toponium might be very suitable for the study of the $B^0 - \bar{B}^0$ mixing because of its clean signature accompanied with a low background.

The mass of the top quark m_t (and hence the mass M of the toponium) is not known yet. However the experimental facts accumulated so far indicate that a top quark should have a large mass. The e^+e^- experiments carried out at PETRA, for instance, give a lower limit for the toponium mass of about 45 GeV/c^2 (Ref. 2). For large quark masses it has long being realized that weak decays of constituent quarks will become important[3-7] as the decay width is proportionnal to m_t^5 (when m_t is smaller than the W mass). On the other hand if the mass of the toponium ($M \sim 2m_t$) is close to the Z^0 mass, interference phenomena[8,9] may complicate the investigation of toponium features. The single quark decay mechanism, however, does not interfer with other processes[3,4]. The energy dependence of the corresponding cross section can then by characterized in the vicinity of the toponium mass by a Breit-Wigner type of function. At the resonance the cross section will then be given by[10]

$$\sigma_{SQD} = \frac{6\pi^2}{M^2} \times \frac{\Gamma_{ee}}{\bar{\sigma}_E} \times \frac{B_{SQD}}{\sqrt{2\pi}}$$

where $B_{SQD} \simeq 2\Gamma_f/\Gamma_t$ is the branching ratio for the weak $t \to f$ (or $\bar{t} \to \bar{f}$) decay having a width of Γ_f and M is the assumed toponium mass. Here Γ_{ee} is the leptonic width of the toponium (in which there is a contribution due the Z^0

pole) whereas Γ_t is its total width, the latter including all the decay channels as well as interference effects. The cm energy dispersion (r.m.s) of the collider is denoted by $\bar{\sigma}_E$. Using the calculations for the various widths given in Ref. 9 we obtain σ_{SQD} as a function of the toponium Z^0 mass difference, as shown in Fig. 1. We assumed that $\bar{\sigma}_E$ scales as E^2, the square of the c.m. energy and that at $E = 100\ GeV$ one has $\bar{\sigma}_E = \bar{\sigma}_{100} = 35\ MeV$ (Ref. 11). Radiative corrections[10] will decrease the shown cross sections by a factor of about 0.45. Note that for a different energy dispersion of the collider the curve of Fig. 1 scales merely as $35/\bar{\sigma}_E(MeV)$.

The detailled structure in the vicinity of the Z^0 mass depends on the specific model choosen to describe the toponium. If instead of the results of Ref. 9 one uses a Richardson type of potential, one obtains results which are similar in magnitude but with a smaller structure around the Z^0 mass[12]. In any case one sees from the Fig. 1 that one obtains rather sizeable cross sections for toponium in the $60 < M < 110\ GeV/c^2$ mass range. In the following we will investigate how single quark decay in toponium may bring some insight about mixing phenomena.

2 - Mixing

There are various sources of leptons in toponium decaying via SQD. This is shown in Fig. 2 which presents at the quark level various ways of producing leptons. As the t quarks decay essentially at rest, only cuts on the lepton momentum can be utilized in order to select the wanted semileptonically decays. As an example let us consider the decay of an hypothetical toponium having a mass of 70 GeV/c^2. Fig. 3 presents for the SQD case the momentum distributions of leptons coming from the $T \to l\nu X$, $B \to l\nu X$ and $D \to l\nu X$ processes (X meaning anything) as obtained with the help of the LUND Monte Carlo program[13]. The leptons due to the $D \to l\nu X$ decay cluster in the low momentum region whereas those coming from the $T \to l\nu X$ processes are emitted with rather large momenta. This different behavior will allow one to reject leptons coming from the D meson and to select those coming either from the T or B mesons.

As proposed previously for the $B^0 - \bar{B}^0$ (or the $D^0 - \bar{D}^0$) system[14–21], mixing for T^0 mesons could also be observed by detecting like sign dileptons in reactions where T mesons are produced. Toponium decaying via weak interactions could (in principle) also be used for this purpose. Indeed after the t ($\bar{t}$) decay the remaining quark can form (in some cases) with a quark from the sea a $\bar{T}^0$ (T^0) meson which subsequently can decay semileptonically. Here also like sign dileptons could indicate the occurence of mixing, one lepton signing the decay of the $t(\bar{t})$ quark and the other one the decay of the $T(\bar{T})$ meson. The situation is thus less favorable than in reactions above $T\bar{T}$ threshold where mixing can occur for both the T or the $\bar{T}$ mesons[22] whenever they are neutral. The mixing phenomenon is governed by the Pais and Treiman parameter[14] which for the $T^0 - \bar{T}^0$ is given by

$$r_t = \frac{\Gamma(T^0 \to \bar{T}^0 \to l^- \nu X)}{\Gamma(T^0 \to l^+ \nu X)}$$

where Γ is used to denote the corresponding width. As in the conventional models[1] one has $r_t \sim 10^{-6}$, the mixing in the $T^0 - \bar{T}^0$ system would thus be hardly measurable.

In contrast $B^0 - \bar{B}^0$ mixing could be observed much more easily. Indeed by applying a p_l momentum cut in the $3 - 6$ GeV/c region (See below) one is essentially left with leptons coming from T and B decays. Then if B^0 mixing occurs we will (in some cases) have among the events having three or four leptons in the final state, three leptons of the same charge (See Fig. 4). Note that this signature cannot be produced by an eventual $T^0 - \bar{T}^0$ mixing process as can be seen by inspecting Fig. 4. In the following we will examine the possibility of observing $B^0 - \bar{B}^0$ mixing by detecting in the decay of toponium events with three leptons of the same charge in the final state.

To obtain quantitative estimates let us use the following definition. We will assume that the notations $T, t \to l$ and $B, b \to l$ always include the contributions due to τ decays, namely $T, t \to \tau \to l$ and $B, b \to \tau \to l$. Whereas there is practically no phase space suppression in the former case, one has $Br(B, b \to \tau\nu X)/Br(B, b \to l\nu X) \sim 0.07$ (Ref. 4), Br denoting a branching ratio. The cross section $\sigma(3l)$ for producing at least three leptons (any charge combination) coming from the t (and/or $\bar{t}$), the b and the $\bar{b}$ quarks is then simply given by

$$\sigma(3l) = \sigma_{SQD} \times [Br(B \to l)]^2 \times [Br(t \to l) + Br(T \to l)]$$

where $Br(B \to l) = 0.12 \times [2 + 0.07 Br(\tau \to l)]$ (Refs. 23,4). In the above expression the terms $Br(t \to l)$ and $Br(T \to l)$ indicate that the leptons are in fact coming from two different sources. In the first case it is the t (or $\bar{t}$) quark which decays semileptonically. In the second case it is assumed that one quark decays weakly (semileptonically or not) whereas the other one forms a T meson which subsequently decays semileptonically. For the present discussion we will assume the validity of the spectator model, hence $Br(t \to l) = Br(T \to l)$. Using $Br(t \to l) \sim 2/9$ and $Br(t \to \tau) \sim Br(t \to l)/2$ (Ref. 24) with $Br(\tau \to l) = 2 \times 0.18$ (Ref. 23) one obtains that $\sigma(3l)$ is in the pb region (See the Table) for $70 < M < 110$ GeV/c^2 and might therefore be accessible to experimental measurements.

Measuring the $B^0 - \bar{B}^0$ mixing by the number of three leptons of the same charge in the final state and neglecting B_c production[25] (as well as any CP violation effect) one has:

$$\begin{aligned} R_m^l = \frac{N^{+++} + N^{---}}{N_d} &= [Br(B \to l)]^2 \times [Br(t \to l) + Br(T \to l)] \times \\ &[2P_u P_d \frac{r_d}{1+r_d} + 2P_d^2 \frac{r_d}{(1+r_d)^2} \\ &+ 2P_s^2 \frac{r_s}{(1+r_s)^2} + 2P_s P_u \frac{r_s}{1+r_s} \\ &+ 2P_d P_s (\frac{r_s}{(1+r_d)(1+r_s)} + \frac{r_d}{(1+r_d)(1+r_s)})] \end{aligned}$$

where r_d and r_s are the Pais and Treiman parameters associated to the B_d^0 and

B_s^0, respectively. Here P_{q_j} is the probability to extract a quark q_j from the sea. Throughout we use $P_s = 0.17$ and $P_u = P_d = (1 - P_s)/2$ (Ref. 21).

Strictly speaking the r_d and r_s parameters depend on the m_t mass (and also on unknown parameters such as the B meson decay constant, the bag parameter and the CP violating phase in the Kobayashi Maskawa matrix). In current models r_d is believed to be of the order of 10^{-2} (Ref. 18) and $r_s \sim 0.4 - 0.9$ (Refs. 20,26). In Ref. 26 upper and lower limits for r_s were calculated as a functions of m_t for a given set of parameters governing the mixing phenomenon. As in all these predictions one has $r_s \gg r_d$, R'_m will scale approximatively as $r_s/(1 + r_s)$. Moreover similarly to the case of the $e^+e^- \rightarrow B\bar{B}X$ in the continuum[21] an observed effect will (in the standard model approach) almost entirely result from the B_s^0 production. To obtain orders of magnitude we will use $r_d = 2.8\ 10^{-2}$ and $r_s = 0.9$ (Refs. 18,20) yielding

$$R'_m = 0.17 \times [Br(B \rightarrow l)]^2 \times [Br(t \rightarrow l) + Br(T \rightarrow l)]$$

(the signal being $\sigma_{SQD} \times R'_m$). For smaller r_s values the expected signal can easily be obtained from the formula giving R'_m or by using the scaling behavior just mentioned.

For convenience we will consider an e^+e^- experiment with a total accumulated luminosity of 200 pb^{-1} (Ref. 27). Using the radiatively corrected σ_{SQD} cross section[10] (See Fig. 1), R'_m, and the values of the branching ratios given above we obtained the expected number of events which, because of $B^0 - \bar{B}^0$ mixing, have three leptons of the same charge in the final state. These numbers are given in the Table for several possible values of the toponium mass and using different cuts for the lepton momentum p_l. All the estimations were made with the help of the Lund Monte Carlo program assuming that the leptons above 3 GeV/c are detected in the $|cos\theta_l| < 0.9$ range with a detection efficiency of $\sim 90\%$ (θ_l is the emission angle of the leptons defined with respect to the beam direction). The tagging efficiencies given in the Table are obtained from a Monte

Carlo calculation taking into account that the various p_l cuts have a different effect for direct $(T, B \to l)$ and secondary $(T, B \to \tau \to l)$ leptons.

In the Table are also given the number of events expected from various backround sources. The backgrounds which we considered are due to:

1. the leptons coming from the D and F mesons and which are not completely eliminated by the p_l cuts,
2. events having two $l^{\pm}$ and a $\pi^{\pm}$ faking a lepton and due to the decay of toponium,
3. events having two $l^{\pm}$ and a $\pi^{\pm}$ faking a lepton but resulting from the decay of the Z^0 or from the continuum.

We assumed a (rather conservative) probability of 10^{-3} that a $\pi^{\pm}$ (or a $K^{\pm}$) will fake a lepton[28] in the considered p_l range. Nevertheless, in practice the p_l cut has to be optimized for the detector which will be used for the experiment.

We noticed from our Monte Carlo investigation that the backgrounds 2. and 3. are only due to the $e^+e^- \to b\bar{b}$ process. We therefore have first considered the $(t\bar{t}) \to b\bar{b}$ for case 2.. This can occur via SQD or through decays involving photon, Z^0 and W exchanges[4,6] i.e. $(t\bar{t}) \to \gamma, W, Z \to b\bar{b}$. For this latter case we took the $(t\bar{t}) \to \Sigma q\bar{q}$ branching ratio from Ref. 9, evaluating the $(t\bar{t}) \to b\bar{b}$ part by means of the formalism described in Refs. 4 and 6. Moreover we assumed that the $(t\bar{t}) \to b\bar{b} \to X$ cross section can be described by a Breit Wigner function in the vicinity of the toponium mass and that one can apply the usual procedure[10] for taking into account radiative corrections and the energy resolution of the collider. We neglected the 3 gluon decay of the toponium (its branching ratio is smaller than the SQD one, see Refs. 3,6), which should in any case give a negligible contribution to the $(t\bar{t}) \to b\bar{b}X$ process. The case of background 3. was handled by assuming that the Z^0 peak cross section is $\sim 30\ nb$ (Ref. 29) and that the Z^0 width is $\sim 2.6\ GeV/c^2$. This latter value does not include the contribution of the $Z^0 \to t\bar{t}$ decay (for the cases where $2M$ is smaller than the Z^0 mass) which is small because of phase space suppression[30]. For the present estimates the background due to the Z^0 ($e^+e^- \to Z^0 \to b\bar{b}$) and the continuum ($e^+e^- \to \gamma \to b\bar{b}$) were added incoherently.

We see from the Table that although the expected signals are not very large the background is very small leading thus to large signal to background (S/B) ratios. In the vicinity of the Z^0 mass where the background 3. is particularly importrant higher p_l cuts were used. This reduces the number of events but leads to S/B ratios comparable to the other cases.

2 - Discussion and Conclusions

The detection of $B^0 - \bar{B}^0$ mixing via like sign leptons has been widely discussed previously either by studying the $e^+e^- \to \Upsilon(4S) \to B_d^0\bar{B}_d^0$ process[15–21] or by using the production of $B\bar{B}$ in the continuum[21]. At the $\Upsilon(4S)$ the study of mixing is handicapped by the fact that the Bose Einstein statistics requirement reduces the effect[17] which in any case is expected to be small for the B_d^0. Moreover the presence of a non-spectator contribution in the B decay[31] will lower the B_d^0 semileptonic branching ratio[32] and would therefore decrease the observability of mixing via the detection of like sign leptons[33]. In the continuum the $e^+e^- \to B\bar{B}X$ reaction has a small cross section at high energy. This is, however, compensated by the fact that one produces B_s^0 for which the mixing is expected to be almost complete. In this case one obtains, however, small signal to background ratios[21]. One has therefore to face the difficulty of subtracting a large background from an observed signal leading thus to the introduction of systematic uncertainties.

For the case discussed here above one has the advantage of dealing with a clear signal (3 leptons of the same charge) and a low background. A large amount of data ($\sim 200\ pb^{-1}$) is, however, necessary to obtain a sample of 10 to 16 events according to the above estimations. On the other hand the data for the proposed study can be accumulated while one is investigating the properties of the toponium family. Indeed all the data obtained from the various toponium bound states could be used for the proposed investigation[34]. The present estimates depend crucially on the probability to extract an s quark from the sea and on the Pais and Treiman parameter associated with the B_s^0 meson. Nevertheless, in the framework of the above discussion it appears that single quark decay phenomena could be used as a further alternative to study $B^0 - \bar{B}^0$ mixing if toponium is in the 70 - 110 GeV/c^2 mass range.

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Table - For a 200 pb^{-1} experiment, estimates of the number of events for the signal ($3l^{\pm}$) and background for various possible masses of the toponium ($t\bar{t}$). Here $\sigma(3l)$ is the radiatively corrected 3 lepton (any charge combination) cross section. The tagging efficiencies for several lepton momentum (p_l) cuts are given as well as the expected signal to background (S/B) ratios. The considered background processes are due to imperfect tagging, to ($2l^{\pm} + \pi^{\pm}$) events where a π (or a K) fakes a l, the latter being due to toponium decays or to processes due to the Z^0 or arising from the continuum.

$(t\bar{t})$ mass GeV/c^2	$\sigma(3l)$ pb	$p_l >$ GeV/c	tagging efficiency %	$3l^{\pm}$ events	Background (events) p_l tagging	Background (events) $2l^{\pm} + \pi^{\pm}$ (toponium)	Background (events) $2l^{\pm} + \pi^{\pm}$ ($Z^0 + q\bar{q}$)	S/B
70	1.8	3	37	12	0.73 ± 0.05	$(9.3 \pm 0.1)10^{-2}$	$(9.4 \pm 0.4)10^{-2}$	~ 13
		3.5	30	9	0.25 ± 0.02	$(5.5 \pm 0.1)10^{-2}$	$(5.9 \pm 0.3)10^{-2}$	~ 25
		4	23	7	0.08 ± 0.01	$(3.1 \pm 0.1)10^{-2}$	$(3.5 \pm 0.2)10^{-2}$	~ 47
80	1.3	3	41	10	1.07 ± 0.05	0.127 ± 0.002	0.29 ± 0.01	~ 6.7
		3.5	32	8	0.46 ± 0.03	$(8.0 \pm 0.2)10^{-2}$	0.182 ± 0.008	~ 11
		4	29	7	0.21 ± 0.02	$(5.0 \pm 0.1)10^{-2}$	0.120 ± 0.006	~ 18
90	3.2	4.5	27	16	0.43 ± 0.04	0.65 ± 0.03	1.64 ± 0.09	~ 5.9
		5	22	12	0.27 ± 0.04	0.47 ± 0.03	1.21 ± 0.08	~ 6.2
		6	15	9	0.023 ± 0.007	0.16 ± 0.02	0.42 ± 0.05	~ 15
100	1.7	4	39	12	1.12 ± 0.06	$(9.7 \pm 0.1)10^{-2}$	0.43 ± 0.02	~ 7.3
		4.5	32	10	0.52 ± 0.04	$(6.6 \pm 0.1)10^{-2}$	0.29 ± 0.01	~ 11
		5	27	9	0.25 ± 0.02	$(4.6 \pm 0.1)10^{-2}$	0.21 ± 0.01	~ 18
110	1.4	4	40	10	1.11 ± 0.05	$(6.3 \pm 0.1)10^{-2}$	$(8.2 \pm 0.3)10^{-2}$	~ 8.0
		4.5	35	9	0.63 ± 0.04	$(4.46 \pm 0.09)10^{-2}$	$(6.0 \pm 0.2)10^{-2}$	~ 12
		5	31	8	0.32 ± 0.02	$(3.12 \pm 0.08)10^{-2}$	$(4.3 \pm 0.2)10^{-2}$	~ 20

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24. The ratio $\sim 2/9$ is obtained by neglecting some of the (small) phase space factor corrections and the $W \rightarrow q\bar{q}$ transitions which are not Cabibbo allowed. See for instance L.M. Seghal, Proceedings of the Europhysics Study on Eletroweak Effects at High Energies, Erice (1983) and G. Altarelli CERN TH-3709 preprint (1983). The phase space correction is negligible for the $t \rightarrow \tau$, hence $Br(t \rightarrow \tau) \simeq Br(t \rightarrow l)/2$.

25. We define B_q by the quark content $(b\bar{q})$.

26. I.I. Bigi, PITHA Report 85/10 (1985), to be published in Phys. Lett. B (1985) and private communication.

27. This value can for instance be obtained with a luminosity of $10^{31} cm^{-2} sec^{-1}$, a running time of about 14 months with a running efficiency of about 50%.

28. This is an assumed average as clearly the values can be very different for the case of a π faking an e or a μ.

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30. As long as the phase space factor is important the increase of the Z^0 width will depend on the Z^0 toponium mass difference. The effect is here negligible as at $M \sim 70$ (80) GeV/c^2 the background 3. would decrease by less than 4 (2)% by adding the $Z^0 \to t\bar{t}$ decay. See for instance:
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32. The non-spectator contribution tends to increase the total decay width of the B_d^0 but practically does not not affect that of the B_u (See for instance 21.) leading thus to a decrease of the B_d^0 semileptonic branching ratio.

33. The $Br(B_s^0 \to l)$ is not expected to be greatly affected by a non-spectator contribution (See 21.). Therefore $(b\bar{b})$ resonances above the $\Upsilon(4S)$ and decaying into B_s^0 might also be very useful for studying $B_s^0 - \bar{B}_s^0$ mixing.

34. For toponium where the bound states are in the vicinity of the Z^0 mass the ratios Γ_{ee}/Γ_t for these states will be nearly equal and given by the ratio obtained at the Z^0 resonance. One has then $\sigma_{SQD} \simeq \Gamma_f(SQD)/M^2$. As Γ_f is increasing with M one expects similar SQD contributions for all the $(t\bar{t})$ bound states.

FIGURE CAPTIONS

Fig. 1 - The single quark decay cross section in toponium as a function of the toponium Z^0 mass difference. The points are calculated assuming that the energy dispersion of the collider is $\bar{\sigma}_E \sim E^2$ (See text). Radiative corrections will decrease the cross sections by a factor of ~ 0.45. The line is drawn to guide the eye.

Fig. 2 - Schematic representation of quark decays which may lead to lepton production.

Fig. 3 - Lepton momentum distributions from D, B and T mesons due to the decays of toponium with an assumed mass of 70 GeV/c^2.

Fig. 4 - Example of a $B^0 \to \bar{B}^0$ process appearing in toponium decays and which could be detected by the $3l^{\pm}$ signature ($3l^{\pm}$ among 4 or 3 leptons in the final state). Note that if the $\bar{t}$ quark would decay semileptonically instead of the the t one the mixing process will not be detected by our selection criteria. Similar diagrams can of course be drawn for the $\bar{B}^0 \to B^0$ case.

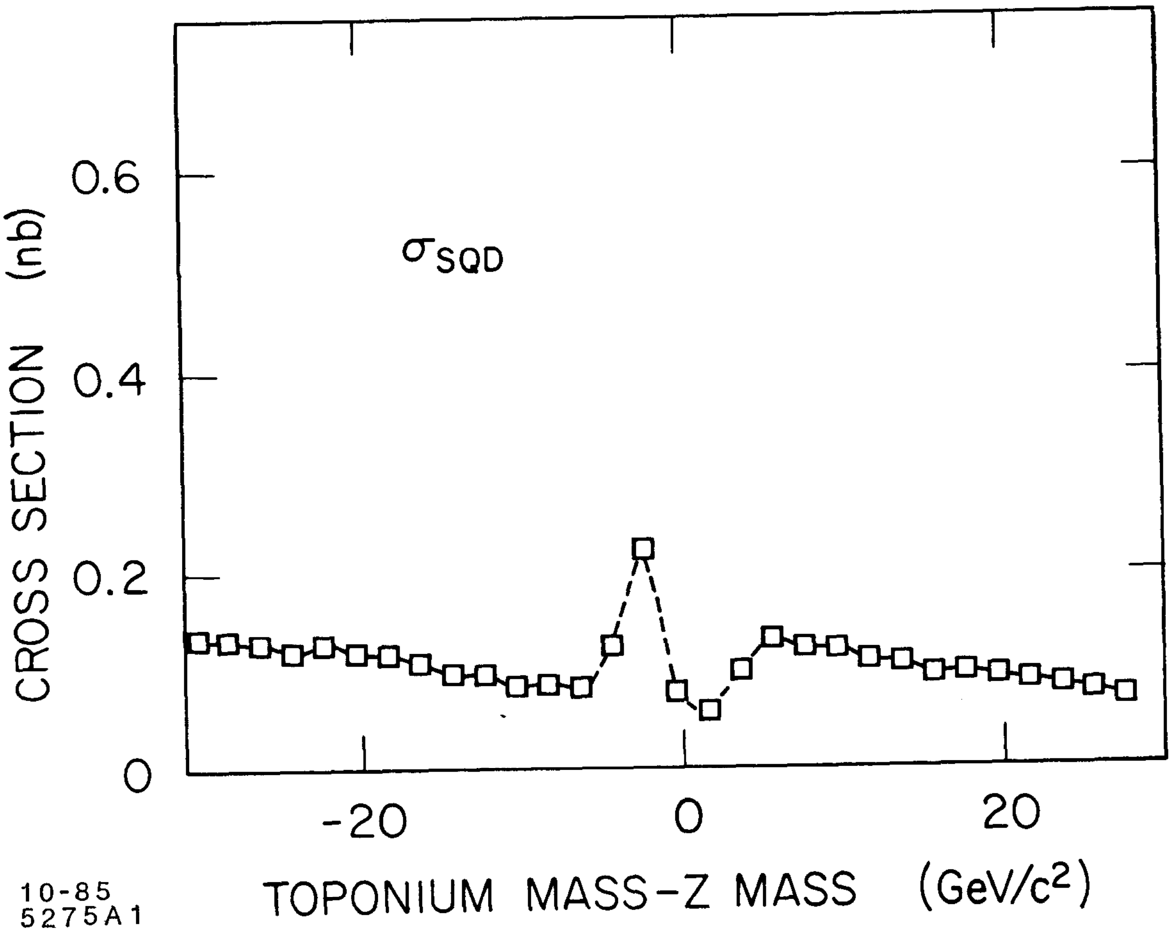
0.6
0.4
0.2
0
CROSS SECTION (nb)
σ_{SQD}
-20
0
20
TOPONIUM MASS-Z MASS (GeV/c²)
10-85
5275A1

Fig. 1

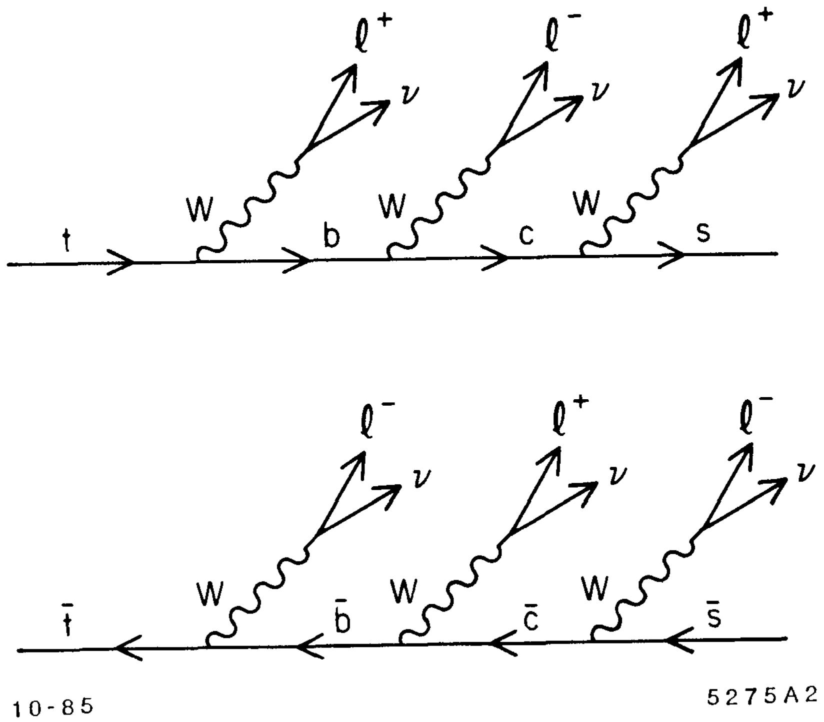

Fig. 2

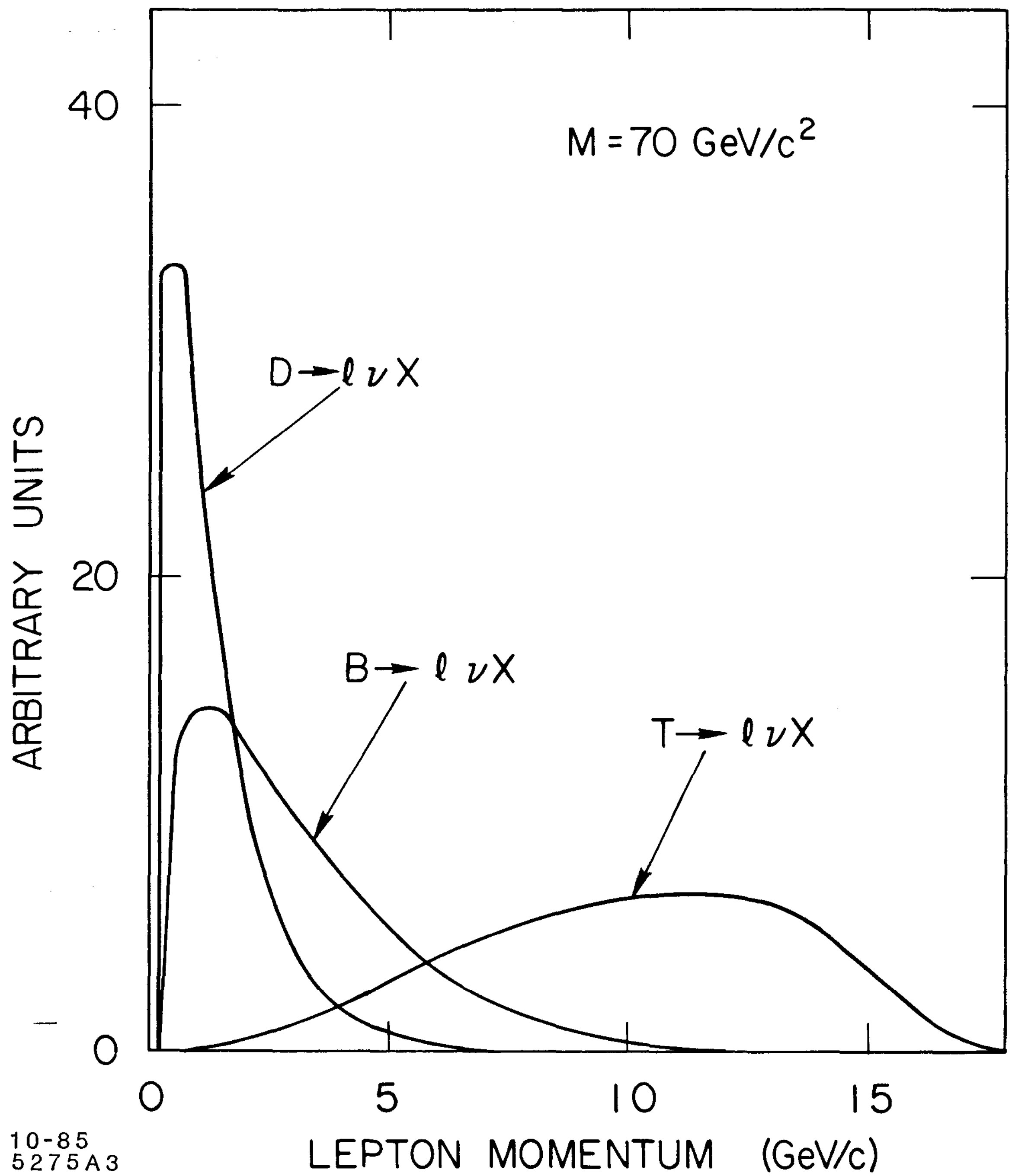
M = 70 GeV/c²
D → ℓνX
B → ℓνX
T → ℓνX
ARBITRARY UNITS
0
20
40
0
5
10
15
LEPTON MOMENTUM (GeV/c)
10-85
5275A3

Fig. 3

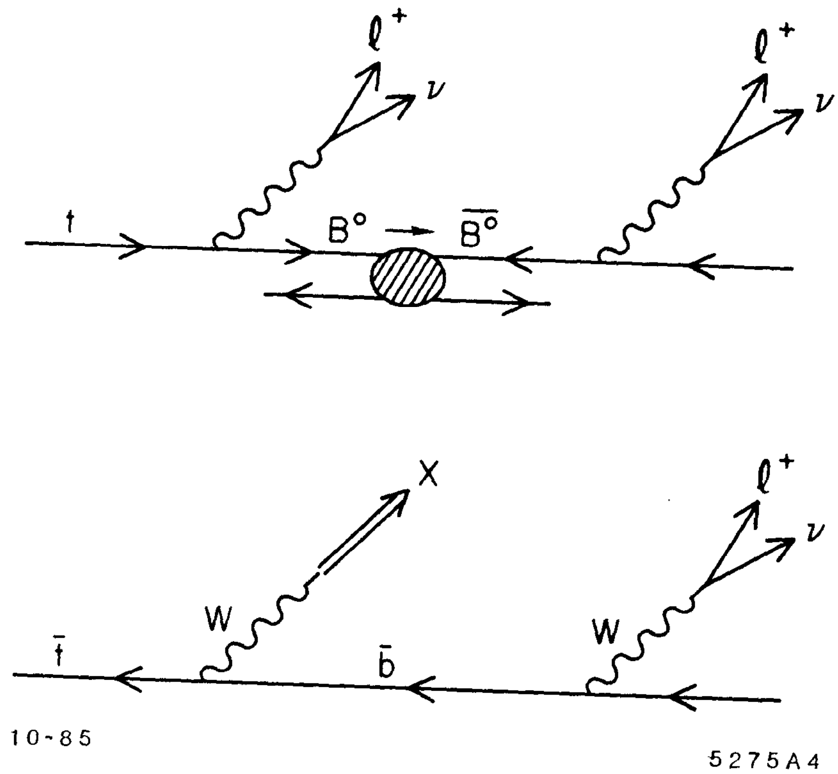

Fig. 4