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INDIRECT SEARCHES FOR LEPTOQUARKS AT PRESENT AND FUTURE COLLIDERS

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We explore the sensitivities of e^+e^- colliders (LEP, CLIC) and hadron-hadron colliders (CERN $\bar{p}p$, FNAL $\bar{p}p$, LHC pp and SSC pp) to the indirect effects of virtual scalar particles with superstring-inspired leptoquark and diquark couplings. We find that e^+e^- colliders have better sensitivities via total cross section measurements of $e^+e^- \to q\bar{q}$ than via asymmetry measurements, and that LEP 2 is much more sensitive than LEP 1. Hadron-hadron colliders are sensitive via lepton-pair production cross sections ($q\bar{q} \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-$).

A perennial theme in particle physics beyond the Standard Model is the possible existence of leptoquarks, i.e., bosons of spin 0 or 1 with couplings to lepton-quark combinations. These have been searched for in e^+e^- collisions — where a lower mass limit of 23 GeV has been established[1] — and more recently in $\bar{p}p$ collisions — where a lower mass limit of 33 GeV for a spin-0 leptoquark decaying into $q + (\mu$ or $\nu)$ has been established.[2] A new variation on the leptoquark theme has been provided by the ten-dimensional heterotic string[3] compactified on some Calabi-Yau manifold.[4] Such models generally contain colour-triplet, SU(2)-singlet, charge-(− 1/3) scalar particles, called here D_0, and their spin-1/2 supersymmetric partners $D_{1/2}$. In addition, there are charge-(+ 1/3), colour-antitriplet conjugate particles[5] D_0^c and $D_{1/2}^c$. These particles may have leptoquark couplings arising from superpotential terms

$$\lambda_l Dlq + \lambda_l^c D^c l^c u^c \qquad (1)$$

and/or diquark couplings arising from superpotential terms

$$\lambda_q Dqq + \lambda_q^c D^c d^c u^c . \qquad (2)$$

It is very dangerous to have both the sets of couplings (1,2), since in combination they can give proton decay via D_0/D_0^c exchange, which could be very rapid if the D_0/D_0^c masses ~ 1 TeV. Accordingly, it is usually assumed that light D particles can have *only* couplings of type (1) *or* of type (2), but *not both.* (See, however, Ref. 6.) If they only have couplings of type (1), the D_0/D_0^c may be regarded as conventional leptoquarks whereas in case

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(2), they would resemble diquarks. In most of this paper, we will concentrate on the leptoquark possibility, discussing searches for indirect effects of the D_0/D_0^c through their virtual exchanges in $e^+e^- \to \bar{q}q$ and $q\bar{q} \to l^+l^-$ processes.[7]

We first discuss the search for indirect leptoquark exchange effects in $e^+e^- \to \bar{q}q$ at SLC or LEP 1 ($\sqrt{s} = 100$ GeV), LEP 2 ($\sqrt{s} = 200$ GeV) and CLIC ($\sqrt{s} = 2$ TeV),[8] expressing our results as regions of the (λ, m_{D_0/D_0^c}) plane which could be excluded by measurements of total cross sections σ and forward-backward asymmetries A at different levels of precision. We find that LEP 1 is very insensitive because of the nearby Z° pole, whereas LEP 2 is sensitive to $m_{D_0/D_0^c} > \sqrt{s}$, particularly through measurements of $\sigma(e^+e^- \to \bar{q}q)$. In the case of hadron-hadron colliders (CERN $\bar{p}p$ at $\sqrt{s} = 630$ GeV, FNAL $\bar{p}p$ at $\sqrt{s} = 1800$ GeV, LHC pp at[9] $\sqrt{s} = 17$ TeV and SSC pp at[10] $\sqrt{s} = 40$ TeV) we concentrate on changes in the different Drell-Yan cross sections ($\bar{q}q \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-$) at the largest values of $M_{l^+l^-}$ for which observable rates are given by the conventional γ^* and $Z^{\circ *}$ exchanges. We again find that there is sensitivity to values of m_{D_0/D_0^c} which are inaccessible to direct searches.

The D_0/D_0^c contributions to $e^+e^- \to \bar{q}q$ come from exchanges of these particles in the crossed channel. The inclusion of these diagrams, in addition to the usual γ and Z exchanges, gives rise to the following additional term in the differential cross section

$$\Delta\left(\frac{d\sigma}{d\cos\theta}\right) = \frac{N_c}{128\pi}(\lambda_{LQ})^2 e^2 \frac{s}{(t-m_D^2)}\left[-\frac{q_u}{s} + \frac{q^z_{u_L} q^z_{e_L} + q^z_{u_R} q^z_{e_R}}{\sin^2\theta_w \cos^2\theta_w (s - m_z^2)}\right] \times (1+\cos\theta)^2 + \frac{N_c}{256\pi}(\lambda_{LQ})^4 \frac{1}{(t-m_D^2)^2}(1-\cos\theta)^2 \tag{3}$$

where

$$N_c = 3, \qquad t = -\frac{s}{2}(1-\cos\theta), \qquad q_u = \frac{2}{3};$$

$$q^z_{u_L} = \frac{1}{2} - \frac{2}{3}\sin^2\theta_w, \qquad q^z_{u_R} = -\frac{2}{3}\sin^2\theta_w,$$

$$q^z_{e_L} = -\frac{1}{2} + \sin^2\theta_w, \qquad q^z_{e_R} = \sin^2\theta_w. \tag{4}$$

and we have assumed one D_0/D_0^c pair with degenerate masses, and that the couplings $\lambda_l = \lambda_l^c \equiv \lambda_{LQ}$.

In Figs. 1a and b, we plot contours of $\Delta\sigma/\sigma$ in the (m_D, λ_{LQ}) plane, where $\sigma = \Sigma_{\text{all } q}\, \sigma(e^+e^- \to \bar{q}q)$ including D-exchange, and $\Delta\sigma$ is obtained from (3) by integrating over θ. Since we are interested only in indirect signatures of the D's, we only plot contours for $m_D \geqslant \sqrt{s}$. We have chosen two values of $\sqrt{s}$: 200 GeV (LEP 2) shown in Fig. 1a, and $\sqrt{s} = 2{,}000$ GeV (CLIC) shown in Fig. 1b. The indirect effects of D-exchange at LEP 1 are not so interesting because the cross section is dominated by the

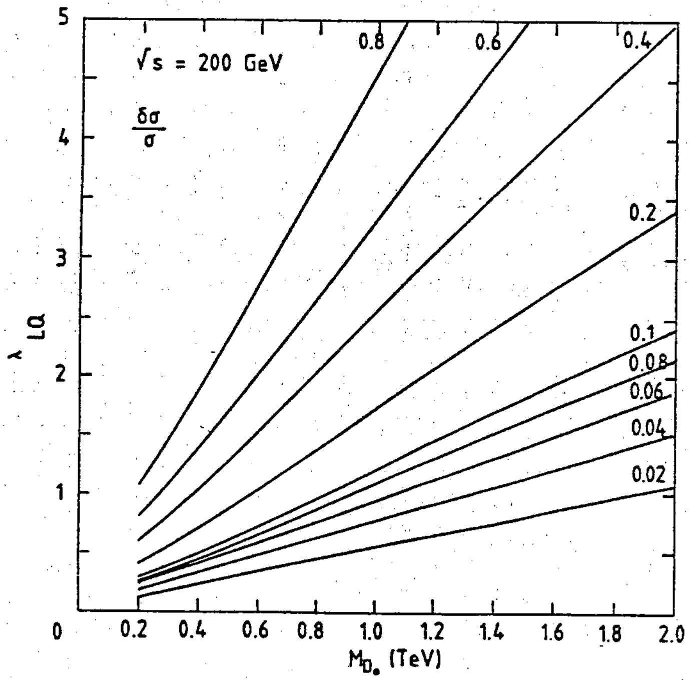
Z peak. One must go off-peak to gain sensitivity to D-exchange, whose main contribution comes from the interference terms in (3). From Figs. 1a and b, we see that a sensitivity to $\Delta\sigma/\sigma = 0.02$ would lead to the discovery limits for m_D which are shown in Table 1 for different values of λ_{LQ}. We show in Figs. 1c and d the corresponding changes in the forward-backward asymmetry, which seems to be less sensitive to D-exchanges: $\delta A = 0.02$ corresponds to $m_D = 0.3$ TeV (3 TeV) at $\sqrt{s} = 200$ GeV (2 TeV) for $\lambda_{LQ} = 1$.

Next we calculate the contribution of D-exchange to $\sigma(\text{hadron} + \text{hadron} \to l^+l^- + X)$ due to the parton process $\bar{u}u \to l^+l^-$,[7] which is the inverse of the previous process. As before, the main contribution comes from the interferences with γ and Z exchange. We present our results in the following way: for each accelerator (CERN $\bar{p}p$: $\sqrt{s} = 630$ GeV, FNAL $\bar{p}p$: $\sqrt{s} = 1.8$ TeV, LHC pp: $\sqrt{s} = 17$ TeV and SSC pp: $\sqrt{s} = 40$ TeV) with the corresponding integrated luminosity (10^{37} cm^{-2}, 10^{37} cm^{-2}, 10^{40} cm^{-2}, 10^{40} cm^{-2}), we first choose the value of the invariant mass $M_{l^+l^-}$ of the l^+l^-pair which corresponds a minimum observable $d\sigma/dM^2_{l^+l^-}$ (~ 1 event/year) for the usual Drell Yan process. These are $M_{l^+l^-} = 0.175$, 0.200, 1.0, 1.2 TeV respectively. Then, working with the value of $M_{l^+l^-}$ so chosen, we obtain the contours of $\Delta\sigma/\sigma$ in the (m_D, λ_{LQ}) plane shown in Fig. 3. From these graphs, we can obtain (for example) lower bounds on m_D if we assume $\lambda_{LQ} = 1$ and demand that $\Delta\sigma/\sigma \leqslant 1$. These limits are shown in Table 2 together with the corresponding upper bounds on the λ_{LQ} obtained if one assumes $m_D \leqslant 1$ TeV. Comparing Tables 1 and 2, we infer that LEP 2 has comparable sensitivity to the highest energy hadron-hadron colliders, whilst the present CERN and FNAL colliders are much less sensitive, and CLIC would be much more sensitive.

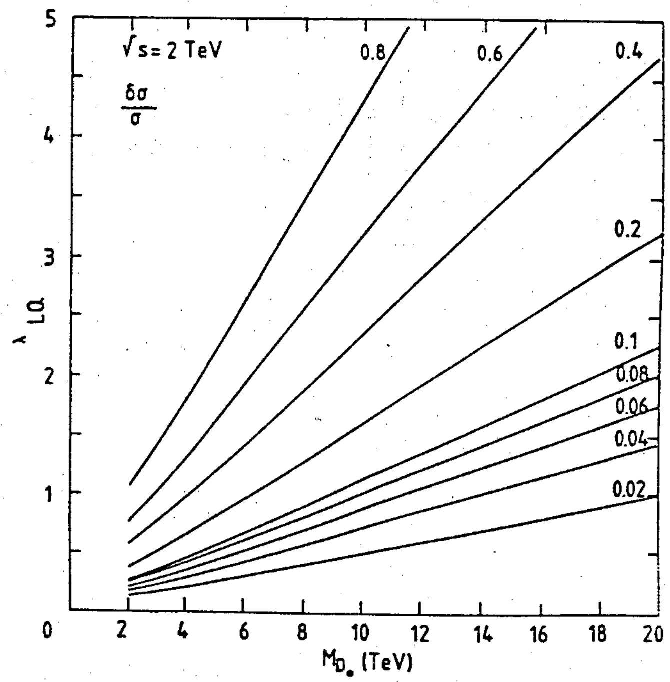
The results of this paper indicate that e^+e^- and hadron-hadron colliders have considerable sensitivity to leptoquark particles with masses larger than those accessible to direct production. We have presented cross section calculations in a superstring-inspired model, although the results have more general validity. Since some superstring-inspired models[4] expect leptoquark masses $m_{D_0/D_0^c} \sim 1$ TeV,[5] and future colliders have sensitivities beyond this mass, such indirect searches for leptoquarks are very topical and relevant.

TABLE 1. Sensitivity in e^+e^- collisions.

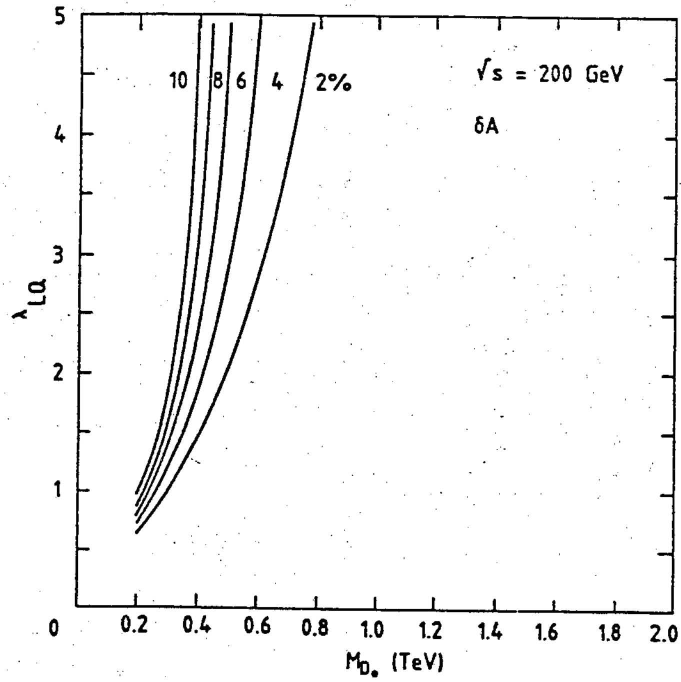
$\sqrt{s}$	200 GeV	2 TeV
λ_{LQ}	m_{D_0} (TeV)	m_{D_0} (TeV)
0.3	< 0.5	< 6.0
0.5	< 0.9	< 9.0
1.0	< 1.8	< 20


√s = 200 GeV
δσ/σ
0.8
0.6
0.4
0.2
0.1
0.08
0.06
0.04
0.02
λ LQ
M_{D_e} (TeV)
0
1
2
3
4
5
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

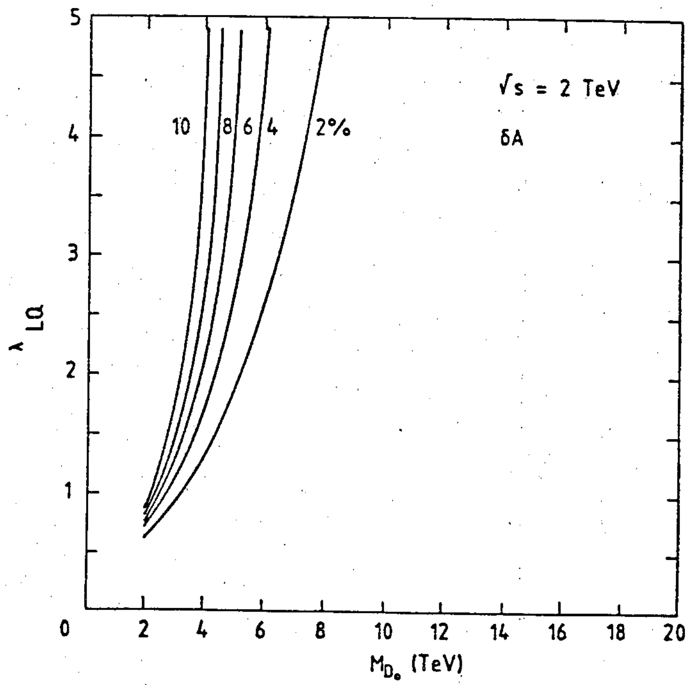
(a)


√s = 2 TeV
δσ/σ
0.8
0.6
0.4
0.2
0.1
0.08
0.06
0.04
0.02
λ LQ
M_{D_e} (TeV)
0
1
2
3
4
5
2
4
6
8
10
12
14
16
18
20

(b)

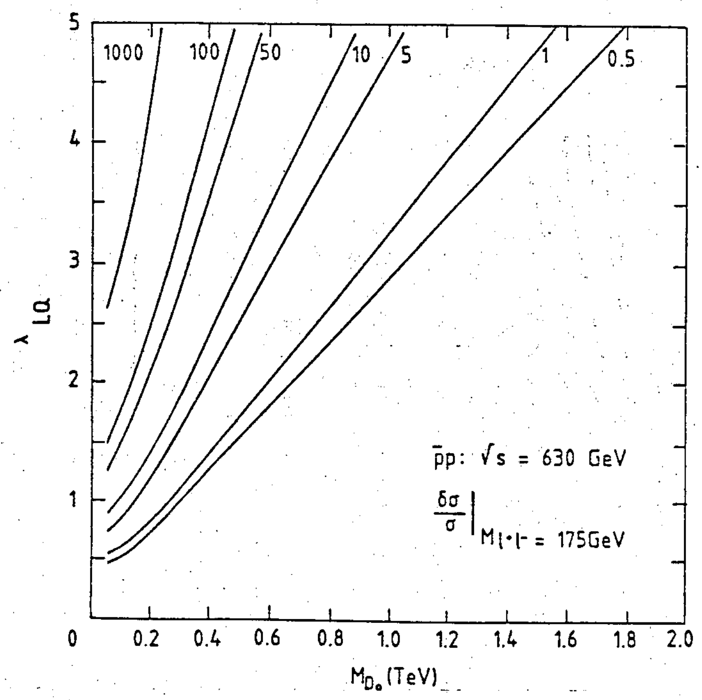


(c)

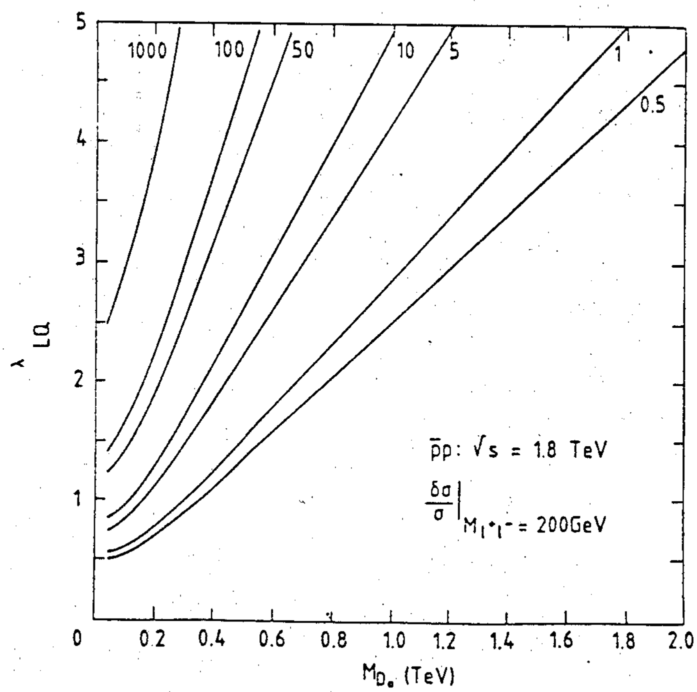


(d)

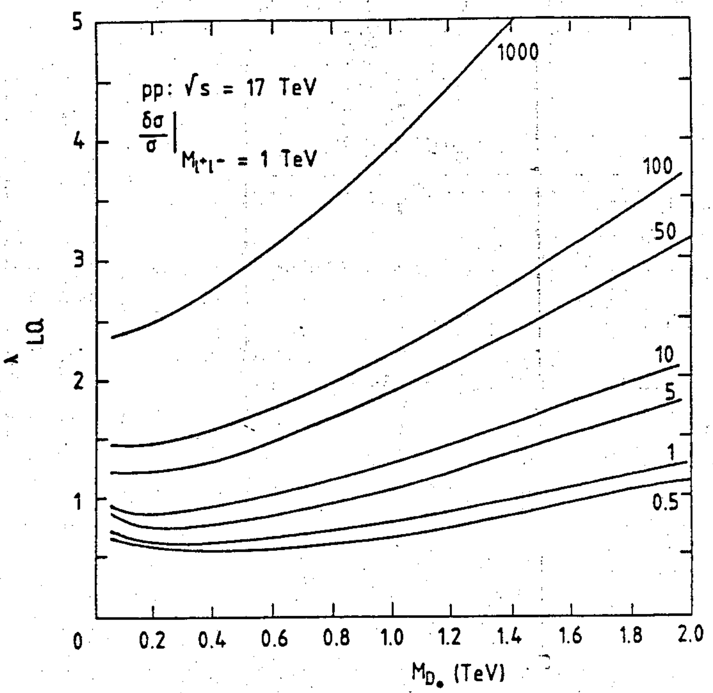
Fig. 1. Indirect effects of leptoquarks in e^+e^- collisions, expressed as contours in the (m_{D_0}, λ_{LQ}) plane, of (a) $\Delta\sigma/\sigma$ at $\sqrt{s} = 200$ GeV (LEP 2), (b) $\Delta\sigma/\sigma$ at $\sqrt{s} = 2$ TeV (CLIC), (c) ΔA at $\sqrt{s} = 200$ GeV (LEP 2), and (d) ΔA at $\sqrt{s} = 2$ TeV (CLIC).


1000
100
50
10
5
1
0.5
$\bar{p}p$: $\sqrt{s}$ = 630 GeV
$\frac{\delta\sigma}{\sigma}\Big|_{M_{l^+l^-}}$ = 175GeV
λ_{LQ}
M_{D_0} (TeV)

(a)

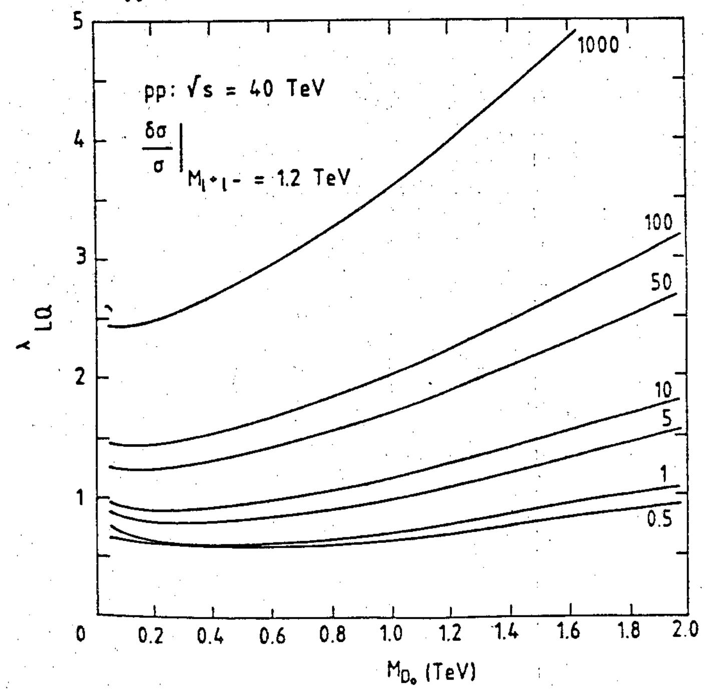

1000
100
50
10
5
1
0.5
$\bar{p}p$: $\sqrt{s}$ = 1.8 TeV
$\frac{\delta\sigma}{\sigma}\Big|_{M_{l^+l^-}}$ = 200GeV
λ_{LQ}
M_{D_0} (TeV)

(b)



(c)

(a)



(d)

(b)

Fig. 2. Indirect effects of leptoquarks in hadron + hadron collisions, expressed as contours in the (m_{D_0}, λ_{LQ}) plane, of $\Delta\sigma/\sigma$ at (a) $\sqrt{s} = 630$ GeV (CERN $\bar{p}p$), (b) $\sqrt{s} = 1.8$ TeV (FNAL $\bar{p}p$), (c) $\sqrt{s} = 17$ TeV (LHC pp), and (d) $\sqrt{s} = 40$ TeV (SSC pp).

TABLE 2. Sensitivity in hadron-hadron collisions assuming $\Delta\sigma/\sigma \geq 1$ at chosen value of $M_{l^+l^-}$.

$\sqrt{s}$ [$M_{l^+l^-}$]	range of m_{D_0} (TeV) for $\lambda_{LQ} = 1$	range of λ_{LQ} for $m_{D_0} = 1$ TeV
630 GeV (CERN) [175 GeV]	< 0.25	< 3.3
1.8 TeV (FNAL) [200 GeV]	< 0.30	< 2.9
17 TeV (LHC) [1 TeV]	< 1.35	< 0.8
40 TeV (SSC) [2 TeV]	< 1.60	< 0.75

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