Looking for spin-$\frac{3}{2}$ leptons in hadronic collisions

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We compute cross sections for the production of spin-$\frac{3}{2}$ leptons in proton-proton collisions, under general assumptions on the coupling of these fermions with ordinary particles. If the compositeness scale is 1–5 TeV and for masses in the range 50–500 GeV these particles will be within the reach of Fermilab Tevatron and the Superconducting Super Collider. We comment on the possible signatures of such leptons.

The standard model of strong and electroweak interactions is in remarkable agreement with the present experimental results. However, the large number of parameters introduced *ad hoc* in the theory can be considered as an indication of the existence of some new physics beyond the standard model. In this larger context some of this arbitrariness would be reduced or tightened, as occurs in grand unified theories, composite models, superstring theories, etc.

If nature, at a deeper level, chooses the possibility in which the fermions are composite, and the constituents are binded by a force similar to the strong-interaction force, we would expect, for example, leptons of spin $\frac{3}{2}$. Actually, there is no experimental evidence against spin-$\frac{3}{2}$ leptons of moderate or large masses (masses up to a few GeV can be ruled out from the results of e^+e^- colliders[1]).

This work is devoted to the study of the production of spin-$\frac{3}{2}$ leptons in hadronic collisions. We shall make use of phenomenological electroweak currents in order to describe the coupling of these leptons to the standard electroweak vector bosons. The reason for doing so is that we do not have renormalizable theories describing the interaction of spin-$\frac{3}{2}$ particles.[2]

We adopt three different phenomenological $V\pm A$ currents involving spin-$\frac{1}{2}$ (ψ) and spin-$\frac{3}{2}$ (χ_μ) fields, consistent with the Rarita-Schwinger theory:[3]

$$J^{\mathrm{I}}_{\mu,i}=\bar{\chi}_\mu(p_1)(c_i+\tilde{c}_i\gamma_5)\psi(p_2)\ , \tag{1a}$$

$$J^{\mathrm{II}}_{\mu,i}=\frac{1}{\Lambda}\bar{\chi}^{\lambda}(p_1)q_\lambda\gamma_\mu(c_i+\tilde{c}_i\gamma_5)\psi(p_2)\ , \tag{1b}$$

$$J^{\mathrm{III}}_{\mu,i}=\frac{1}{\Lambda^2}\bar{\chi}^{\lambda}(p_1)q_\lambda i\sigma_{\mu\beta}q^{\beta}(c_i+\tilde{c}_i\gamma_5)\psi(p_2)\ , \tag{1c}$$

where $q=p_1+p_2$, and the mass scale Λ should be related to a compositeness scale, or to the spin-$\frac{3}{2}$-lepton mass (if we assume them fundamental). The currents (1a) to (1c) are built up with operators of increasing dimensionality. Other forms (with the same dimension) could be found, but it is possible to show that they can be reduced to the three above.[3] We assume that the different electroweak vector bosons couple to the currents (1a)–(1c) according to $J_{\mu,i}V^\mu_i$ ($V^\mu_i=A^\mu,Z^\mu,W^\mu$) with strengths c_i and $\tilde{c}_i$ which can be different for each vector boson (hereafter, these constants will be referred as c_γ, $\tilde{c}_\gamma$, c_Z, $\tilde{c}_Z$, c_W, and $\tilde{c}_W$).

We shall be considering a scheme identical to that proposed by Lopes *et al.*,[1] associating to each usual lepton doublet $(\nu,l)_{1/2}$ a spin-$\frac{3}{2}$ doublet $(\mathcal{N},\mathcal{L})_{3/2}$ which carries the same leptonic number. Furthermore we do not allow intergenerational transitions in order to eliminate flavor-changing neutral currents which are quite constrained by low-energy experiments.

We will study the production of a spin-$\frac{3}{2}$ lepton in hadronic collisions through the Drell-Yan mechanism as a result of the subprocesses (depicted in Fig. 1)

$$q\bar{q}\to\gamma\ ,\quad Z\to\mathcal{L}^{\pm}l^{\mp}\ , \tag{2a}$$

$$q\bar{q}'\to W^{\pm}\to\mathcal{L}^{\pm}\overset{(-)}{\nu}\ . \tag{2b}$$

We compute the rapidity distribution at $y=0$ for the process $pp\to\mathcal{L}^{\pm}l^{\mp}(\mathcal{L}^{\pm}\overset{(-)}{\nu})+X$. This quantity gives a good estimate of the total cross section, because the rapidity distribution is flat in the considered range. In terms of the quark distribution functions (f^i_h) and neglecting the spin-$\frac{1}{2}$-lepton masses the rapidity distribution is written as

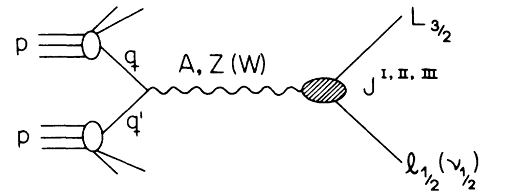

FIG. 1. Drell-Yan mechanism for the production of a pair spin-$\frac{3}{2}$–spin-$\frac{1}{2}$ leptons.

$$\left.\frac{d\sigma}{dy}\right|_{y=0}^{pp\to\mathcal{L}l(\mathcal{L}\nu)}$$
$$=2\sum_{ij}\int_{M^2/s}^{1}d\tau[f_p^i(\sqrt{\tau})f_p^j(\sqrt{\tau})]\hat\sigma_{q_iq_j\to\mathcal{L}l(\mathcal{L}\nu)}(\hat s)\ , \quad (3)$$

where $\hat\sigma(\hat s=\tau s)$ is the total cross section for the subprocesses (2a) or (2b) and M is the spin-$\frac{3}{2}$ mass. For the quarks distribution functions we have taken the set 2 of Ref. 4, whereas the cross sections for the subprocesses (2) computed for each current (1) are listed below.

For the neutral-current subprocesses (2a) we have

$$\hat\sigma^{\mathrm{I}}_{\mathcal{L}l}=(A\alpha/9)\frac{(1-\eta)^2}{\hat s\eta}(1+10\eta+\eta^2)\ , \quad (4a)$$

$$\hat\sigma^{\mathrm{II}}_{\mathcal{L}l}=(A\alpha/9\Lambda^2)\frac{(1-\eta)^4}{\eta}(2+\eta)\ , \quad (4b)$$

$$\sigma^{\mathrm{III}}_{\mathcal{L}l}=(A\alpha/9\Lambda^4)\frac{\hat s(1-\eta)^4}{\eta}(1+2\eta)\ , \quad (4c)$$

where $\alpha=e^2/4\pi$, $\eta=M^2/\hat s$, and

$$A=(c_\gamma{}^2+\tilde c_\gamma{}^2)+\frac{2c_V(c_Zc_\gamma+\tilde c_Z\tilde c_\gamma)}{(\hat s-M_Z{}^2)^2+\Gamma_Z{}^2M_Z{}^2}\hat s(\hat s-M_Z{}^2)$$
$$+\frac{(c_V{}^2+c_A{}^2)(c_Z{}^2+\tilde c_Z{}^2)}{(\hat s-M_Z{}^2)^2+\Gamma_Z{}^2M_Z{}^2}\hat s^2\ , \quad (5)$$

where c_V (c_A) is the vector (axial-vector) coupling of the quarks to the electroweak bosons

$$c_V=\frac{1}{\sin\theta_W\cos\theta_W}(\tfrac{1}{2}T_{3L}-Q\sin^2\theta_W)\ ,$$

$$c_A=\frac{-1}{\sin\theta_W\cos\theta_W}(\tfrac{1}{2}T_{3L})\ .$$

For the charged-current subprocess (2b) we have obtained

$$\hat\sigma^{\mathrm{I}}_{\mathcal{L}\nu}=\frac{\alpha(c_W{}^2+\tilde c_W{}^2)}{432\sin^2\theta_W}\frac{\hat s}{(\hat s-M^2)^2+\Gamma_W{}^2M_W{}^2}(1-\eta)^2\left[10+\eta+\frac{1}{\eta}\right]\ , \quad (6a)$$

$$\hat\sigma^{\mathrm{II}}_{\mathcal{L}\nu}=\frac{(\alpha/\Lambda^2)(c_W{}^2+\tilde c_W{}^2)}{432\sin^2\theta_W}\frac{\hat s^2}{(\hat s-M_W{}^2)^2+\Gamma_W{}^2M_W{}^2}\frac{(1-\eta)^3}{\eta}(2-\eta-\eta^2)\ , \quad (6b)$$

$$\hat\sigma^{\mathrm{III}}_{\mathcal{L}\nu}=\frac{(\alpha/\Lambda^4)(c_W{}^2+\tilde c_W{}^2)}{432\sin^2\theta_W}\frac{\hat s^3}{(\hat s-M_W{}^2)^2+\Gamma_W{}^2M_W{}^2}\frac{(1-\eta)^4}{\eta}(1+2\eta)\ . \quad (6c)$$

As expected, the nonrenormalizable phenomenological theory lead us to cross sections that violates unitarity. An estimate of the values of $\hat s$ up to which the cross sections (4) and (6) are meaningful, can be obtained by imposing saturation of the unitarity bound. We have obtained the following range of energies for each type of current (I, II, and III):

Current	γ-Z	W
I	$\hat s\lesssim 10^9M^2/B$	$\hat s\lesssim 10^5M^2/C$
II	$\hat s\lesssim 10^4M\Lambda/B^{1/2}$	$\hat s\lesssim 10^2M\Lambda/C^{1/2}$
III	$\hat s\lesssim 10^3(M^2\Lambda^4/B)^{1/3}$	$\hat s\lesssim 10^1(M^2\Lambda^4/C)^{1/3}$

where B and C are given by

$$B=(c_\gamma{}^2+\tilde c_\gamma{}^2)+(c_V{}^2+c_A{}^2)(c_Z{}^2+\tilde c_Z{}^2)$$
$$+2c_V(c_Zc_\gamma+\tilde c_Z\tilde c_\gamma)\ ,$$
$$C=c_W{}^2+\tilde c_W{}^2\ ,$$

and we have taken $\sin^2\theta_W=0.226$. Above these values we have assumed that the cross sections for the subprocesses fall as $1/\hat s$. We have checked that our numerical results do not change in a significant way, in the range of masses and energies considered, even if we allow a deviation from this behavior.

Our results are depicted in Figs. 2–6. We have assumed

$$c_\gamma=e\ ,\quad \tilde c_\gamma=0\ ,$$
$$c_Z=-\tilde c_Z=e/\sin\theta_W\ ,\quad c_W=-\tilde c_W=e\ ,$$

and we have also neglected the $s=\frac{1}{2}$ lepton masses in the calculation. The cross sections of the neutral channel dominates for energies as high as the one of the Fermilab Tevatron (see Figs. 2–4). At energies that will be reached by the proposed Superconducting Super Collider (SSC) both events are of the same order.

The currents associated with operators of lower dimensionality dominate at low energies, but at energies of ~ 10 TeV the situation is reversed: the currents II and III become more important. We also observe a crucial depen-

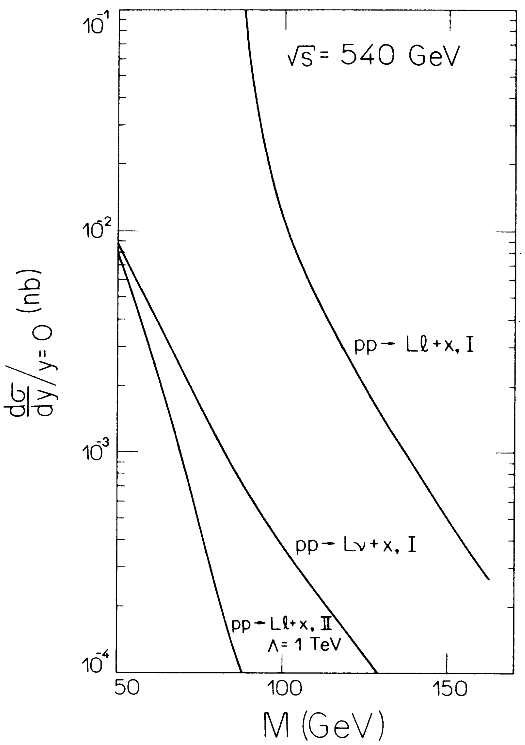

FIG. 2. Rapidity distributions at $y=0$ for processes (2a) and (2b), at $\sqrt{s}=540$ GeV, and for different currents.

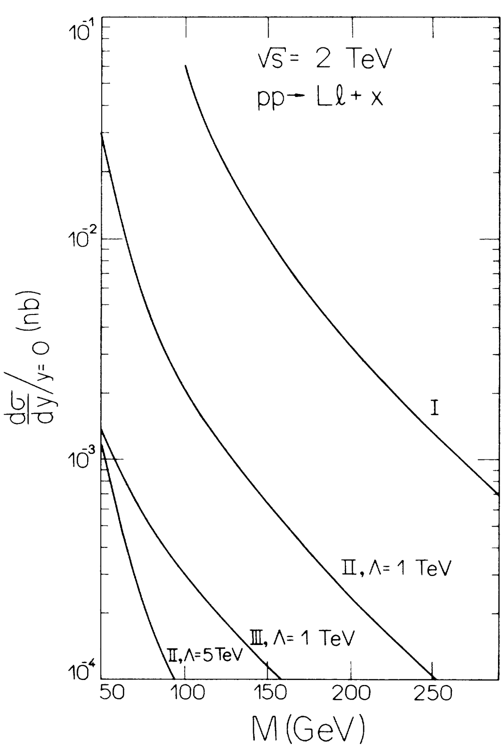

FIG. 3. Rapidity distributions at $y=0$ for the process (2a), at $\sqrt{s}=2$ TeV, for currents I, II, and III with different values of Λ.

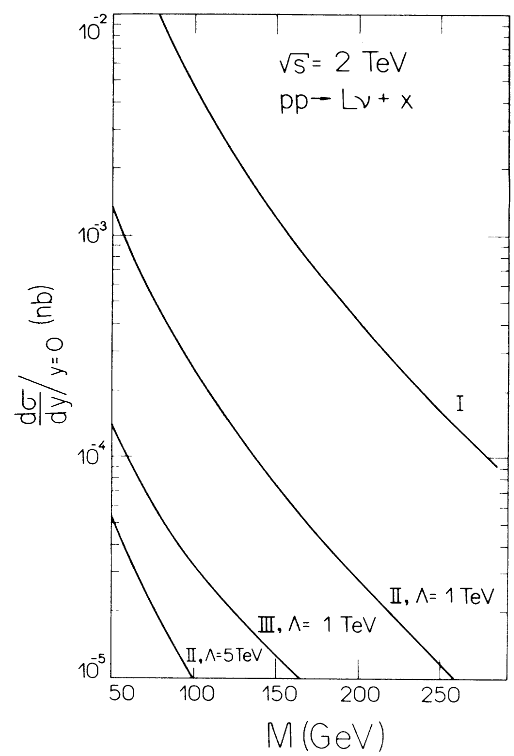

FIG. 4. The same as Fig. 3, for process (2b).

dence on the scale Λ for these two currents. For $\Lambda \sim 1$ TeV we have a real possibility of detecting spin-$\frac{3}{2}$ leptons at energies of the Tevatron and SSC. This is true when they couple to the electroweak bosons through currents II and III, but if Λ increases only current I will be operative. In any case, for $\mathcal{L}$ masses up to 500 GeV, a large number of events/year should be expected in the existent or planned hadronic colliders thus permitting the observation of spin-$\frac{3}{2}$ leptons.

The lepton $\mathcal{L}$ should be searched through its decay into a real weak boson and a light lepton (l or ν) if $\mathcal{L}$ is heavier than M_W, or by looking directly to one event with three charged leptons in one hemisphere and a single charged lepton in the other hemisphere. For example, suppose that the spin-$\frac{3}{2}$ lepton is of the muon type and that it is produced through reaction (2a) with subsequent decay into a μ plus a lepton (l) pair:

$$q\bar{q} \to \mathcal{L}_\mu^- + \mu^+$$
$$\hookrightarrow \mu^- + l^- + l^+ \; .$$

If the leptonic pair ($l^- l^+$) are muons the spectral distribution of this last μ^+ is,[5] for current I,

$$\frac{1}{\Gamma_1}\frac{d\Gamma_1}{dx}(\mathcal{L}_\mu \to 3\mu) = \frac{20}{3}x^2\left[\frac{x^2}{12} - x + 1\right] ,$$

where the muon mass has been neglected when compared to M, and $x = 2E/M$ (E is the energy of the outgoing μ^+). These kind of events may offer a quite distinctive way to look for a possible spin-$\frac{3}{2}$ lepton.

If spin-$\frac{3}{2}$ leptons are found at high-energy hadronic col-

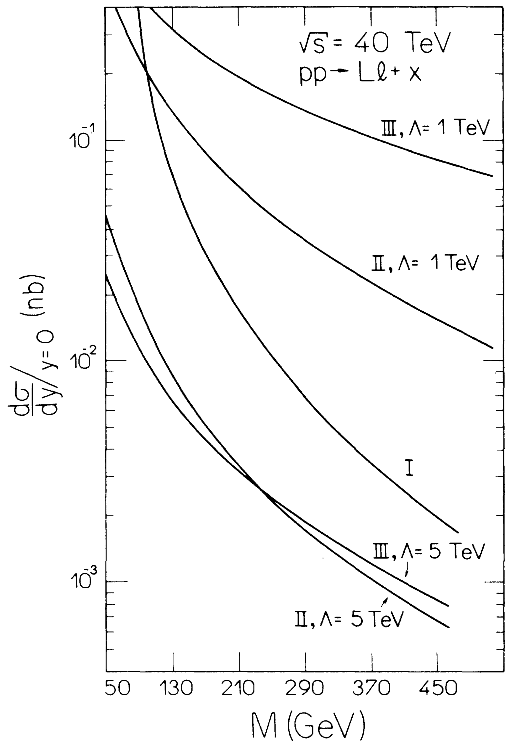

FIG. 5. The same as Fig. 3, for $\sqrt{2}=40$ TeV.

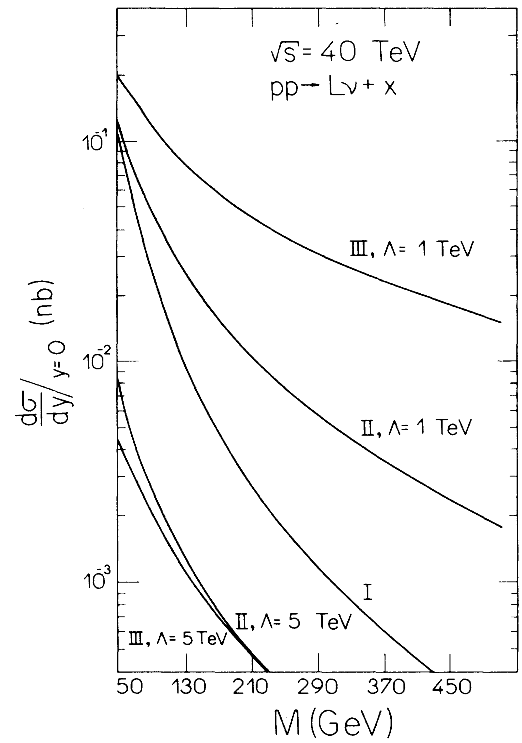

FIG. 6. The same as Fig. 5, for the process (2b).

liders, with a large number of events, it may be interesting to measure other quantities as the transverse-momentum distribution, etc., enabling a more precise determination of the couplings c_i and $\tilde{c}_i$. For this reason, we give in the Appendix the invariant cross sections, from which these quantities can easily be computed.

In conclusion, if the compositeness scale is of the order of 1–5 TeV, the observation of spin-$\frac{3}{2}$ leptons will be within the reach of the Tevatron or the SSC if the spin-$\frac{3}{2}$ particles have masses in the range $50 < M < 500$ GeV. The most promising events are those in which there are three usual leptons in one hemisphere and another lepton at the opposite hemisphere. The measurement of the invariant-mass distribution of the three leptons and the spectral distribution of the lepton having the same charge as the one in the other hemisphere will give a definitive signal for the production of spin-$\frac{3}{2}$ particles.

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APPENDIX

We give here, as a matter of completeness, the invariant cross sections for the subprocesses (2).

For the neutral channel, and each one of the currents (1), we have

$$\frac{d\hat{\sigma}^{\,\mathrm{I}}}{dt}=\frac{4\alpha}{3\pi s^4}\left[A(s-M^2)\left[s+\frac{t}{2M^2}(M^2-s-t)\right]+\frac{B'}{2}s(M^2-2t-s)\right], \tag{A1}$$

$$\frac{d\hat{\sigma}^{\,\mathrm{II}}}{dt}=\frac{\alpha}{3\pi s^4}\frac{(s-M^2)^2}{M^4}\{A[2t^2-2t(M^2-s)-s(M^2-s)]+B's(M^2-s-2t)\}, \tag{A2}$$

$$\frac{d\hat{\sigma}^{\,\mathrm{III}}}{dt}=\frac{\alpha}{3\pi s^4}\frac{1}{M^2}A(s-M^2)^2[(s-M^2)(sM^2-2st)-2st^2], \tag{A3}$$

where

$$B'=\frac{c_V c_A c_Z \tilde{c}_Z}{(\hat{s}-M_Z{}^2)^2+\Gamma_Z{}^2 M_Z{}^2}\hat{s}^2+\frac{2c_A(c_Z c_\gamma+\tilde{c}_Z\tilde{c}_\gamma)}{(\hat{s}-M_Z{}^2)^2+\Gamma_Z{}^2M_Z{}^2}\hat{s}(\hat{s}-M_Z{}^2).$$

For the charged channel, we get

$$\frac{d\hat{\sigma}^{\,\mathrm{I}}}{dt}=\frac{\alpha}{72\pi\sin^2\theta_W}\frac{1}{(s-M^2)^2+\Gamma_W{}^2M_W{}^2}\left[(c_W{}^2+\tilde{c}_W{}^2)\frac{1-\eta}{s^2\eta}[2\eta s^2-t^2-ts(1-\eta)]-2\tilde{c}_W(\eta-1-2t/s)\right], \tag{A4}$$

$$\frac{d\hat{\sigma}^{\,\mathrm{II}}}{dt}=\frac{\alpha}{144\pi\sin^2\theta_W}\frac{(1-\eta)^2}{\eta^2[(s-M_W{}^2)^2+\Gamma_W{}^2M_W{}^2]}\{(c_W{}^2+\tilde{c}_W{}^2)[(1+2t/s)(1-\eta)+2t^2/s]-2\tilde{c}_W(1+2t/s-\eta)\}, \tag{A5}$$

$$\frac{d\hat{\sigma}^{\,\mathrm{III}}}{dt}=\frac{\alpha(c_W{}^2+\tilde{c}_W{}^2)}{144\pi\sin^2\theta_W}\frac{(1-\eta)^2}{(s-M_W{}^2)^2+\Gamma_W{}^2M_W{}^2}\frac{1}{s\eta^3}[(1-\eta)(\eta s-2t)-2t^2/s]. \tag{A6}$$

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