# New Tests for Quark and Lepton Substructure

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If quarks and leptons are composite at the energy scale $\Lambda$, the strong forces binding their constituents induce flavor-diagonal contact interactions, which have significant effects at reaction energies well below $\Lambda$. Consideration of their effect on Bhabha scattering produces a new, stronger bound on the scale of electron compositeness: $\Lambda > 750$ GeV. Collider experiments now being planned will be sensitive to $\Lambda \sim 1$–5 TeV for both electrons and light quarks.

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The proliferation of quarks and leptons has naturally led to the speculation that they are composite structures, bound states of more fundamental constituents which are often called "preons."[1] Many authors have proposed models of such composite structure, but no obviously correct or compelling model has yet emerged. There is not even consensus on the most fundamental aspect of quark and lepton substructure—the value of the mass scale $\Lambda$ which characterizes the strength of preon-binding interactions and the physical size of composite states. It is therefore important to devise experiments which probe this potential substructure as deeply as possible and which, at the same time, test the widest possible variety of models. In this Letter, we identify new observable consequences of quark and lepton substructure which do just that.[2] As immediate result of these is that existing Bhabha-scattering measurements imply that $\Lambda > 750$ GeV for the electron, a factor of 5 larger than previous lower bounds.

Before spelling out our tests, let us review what is known about $\Lambda$. At present, high-energy cross sections are well explained by the standard $SU(3) \otimes SU(2) \otimes U(1)$ gauge theory with elementary quarks and leptons. If these fermions are composite, then $\Lambda$ is much larger than their masses, completely unlike the situation in nuclear and hadron physics. However, 't Hooft has argued that gauge theories of preon binding quite naturally produce composite fermions much less massive than the binding scale provided certain symmetry constraints are satisfied.[3] Since the energy $\Lambda_{EW} = O(1\text{ TeV})$ at which electroweak symmetry is broken is the lowest new dynamical scale we foresee, we expect $\Lambda \gtrsim \Lambda_{EW}$.

Modifications of gauge-field ($\gamma$, $Z^0$, etc.) propagators and vertices with fermions occur in any preon model, though their precise form is model dependent. In a favored parametrization,[4] one simply multiplies the gauge propagator by a form factor $F(q^2) \cong 1 + q^2/\Lambda^2$. Measurements of $e^+e^- \to \psi\bar{\psi}$ ($\psi = e, \mu, \tau, q$) up to $\sqrt{s} = 35$ GeV at PETRA have excluded photon form factors for $\Lambda \lesssim 100$–200 GeV.[5] Composite fermions also possess new contact interactions generated by constituent exchange. These four-fermion interactions have strength $\pm g^2/\Lambda^2$, where $g$ is an effective strong-coupling constant analogous to the $\rho$ coupling $g_\rho^2/4\pi \cong 2.1$. If contact interactions mediate flavor-changing processes such as $K_L^0 \to \mu e$ and $D^0$-$\bar{D}^0$ and $K^0$-$\bar{K}^0$ mixing, the lower limits on $\Lambda$ range from ~30 TeV to ~800 TeV.[6] While these bounds are impressive, it is possible to construct composite models in which some[6] or all[7] of the dangerous flavor-changing interactions are absent. In summary, the only relatively model-independent constraints are the much lower ones deduced from the PETRA measurements.[8]

Our new tests for substructure are based on two observations: *First,* in any model in which one or both chiral components of the fermion $\psi$ is composite, there must occur flavor-diagonal, helicity-conserving contact interactions of the form[9]

$$\mathcal{L}_{\psi\psi}=(g^2/2\Lambda^2)[\eta_{LL}\bar{\psi}_L\gamma_\mu\psi_L\bar{\psi}_L\gamma^\mu\psi_L+\eta_{RR}\bar{\psi}_R\gamma_\mu\psi_R\bar{\psi}_R\gamma^\mu\psi_R+2\eta_{RL}\bar{\psi}_R\gamma_\mu\psi_R\bar{\psi}_L\gamma^\mu\psi_L]. \quad (1)$$

In our construction of Eq. (1), we assume that the standard SU(3) ⊗ SU(2) ⊗ U(1) gauge theory is correct and that $\Lambda \gtrsim \Lambda_{EW}$.[10] Then $\psi_L$ and $\psi_R$ are distinct species and there is no reason why $\mathcal{L}_{\psi\psi}$ should conserve parity. We define $\Lambda$ in Eq. (1) such that the strong coupling $g^2/4\pi=1$ and the largest $|\eta_{if}|=1$. Color indices, if any, are suppressed in Eq. (1). *Second,* if some kinematic region of $\psi$-$\psi$ elastic scattering is, in the standard theory, controlled by a gauge coupling $\alpha_\psi \ll 1$, then $\mathcal{L}_{\psi\psi}$ produces interference terms in the cross section of order $(4\pi\alpha_\psi/q^2)^{-1}(g^2/\Lambda^2)=q^2/\alpha_\psi\Lambda^2$ relative to the standard-model contribution.[11] This model-independent effect overwhelms the $O(q^2/\Lambda^2)$ contribution of form factors.

We apply our tests below to high-energy Bhabha scattering ($\alpha_\psi \Delta \cong \alpha$) and to jet production at high transverse momentum ($p_T$) in hadron-hadron colliders [$\alpha_\psi=\alpha_{QCD}(q^2)$]. It is also important to consider the model-dependent possibility that distinct fermions $\psi_1$ and $\psi_2$ have some constituents in common. Then an interaction such as (1) exists, with roughly the same strength, and will modify cross sections for $\psi_1\bar{\psi}_1 \to \psi_2\bar{\psi}_2$, $\psi_1\psi_2 \to \psi_1\psi_2$ and their $SU(2)_W$ transforms. As an example, we shall consider $e^+e^- \to \mu^+\mu^-$.

*Bhabha scattering.* The unpolarized-beam cross section, including $\gamma$ and $Z^0$ exchanges and $\mathcal{L}_{\psi\psi}$ with $\psi=e$, is given by

$$d\sigma/d(\cos\theta)=(\pi\alpha^2/4s)[4A_0+A_-(1-\cos\theta)^2+A_+(1+\cos\theta)^2];$$

$$A_0=\left(\frac{s}{t}\right)^2\left|1+\frac{g_Rg_L}{e^2}\frac{t}{t_z}+\frac{\eta_{RL}t}{\alpha\Lambda^2}\right|^2,\quad A_-=\left|1+\frac{g_Rg_L}{e^2}\frac{s}{s_z}+\frac{\eta_{RL}s}{\alpha\Lambda^2}\right|^2, \quad (2)$$

$$A_+=\tfrac{1}{2}\left|1+\frac{s}{t}+\frac{g_R^2}{e^2}\left(\frac{s}{s_z}+\frac{s}{t_z}\right)+\frac{2\eta_{RR}s}{\alpha\Lambda^2}\right|^2+\tfrac{1}{2}\left|1+\frac{s}{t}+\frac{g_L^2}{e^2}\left(\frac{s}{s_z}+\frac{s}{t_z}\right)+\frac{2\eta_{LL}s}{\alpha\Lambda^2}\right|^2.$$

In Eq. (2), $t=-s(1-\cos\theta)/2$, $s_z=s-\mu_z^2+i\mu_z\Gamma_z$ and $t_z=t-\mu_z^2+i\mu_z\Gamma_z$; $g_R/e=\tan\theta_W$ and $g_L/e=-\cot 2\theta_W$.[12]

A useful way to search experimentally for electron substructure is to plot the fractional deviation

$$\Delta_{ee}(\cos\theta)=\frac{d\sigma/d(\cos\theta)|_{\text{meas.}}}{d\sigma/d(\cos\theta)|_{EW}}-1, \quad (3)$$

where $d\sigma/d(\cos\theta)|_{EW}$ is given by Eq. (2) with $\Lambda=\infty$. Since $\Lambda_{ee}$ must vanish in the forward direction, the measured cross section can be normalized there to the electroweak value.

We have used Eqs. (2) to calculate $\Lambda_{ee}$ at $\sqrt{s}=35$ GeV for the cases in which $\mathcal{L}_{ee}$ reduces to the coupling of two left-handed (LL), right-handed (RR), vector (VV) and axial-vector (AA) currents. In the LL model, e.g., we have $\eta_{LL}=\pm 1$, $\eta_{RR}=\eta_{RL}=0$. The results are shown in Fig. 1 for values of $\Lambda$ such that $|\Delta_{ee}|\simeq 3\%-5\%$ over a wide angular range, consistent with the PETRA measurements.[5] Several comments are in order: (1) For $s \ll \mu_z^2$, the RR model is indistinguishable from LL, because the parity-nonconserving $Z^0$ terms are negligible there. (2) Greater sensitivity to $\Lambda$ occurs when both left- and right-handed electron components are composite and have common constituents ($|\eta_{RL}|\simeq 1$). (3) Even greater sensitivity to the space-time structure of $\mathcal{L}_{ee}$ may be obtained by using polarized $e^+$, $e^-$ beams.[13] (4) The PETRA measurements imply the bounds

$$\Lambda(\text{LL, RR}) > 750 \text{ GeV};$$
$$\Lambda(\text{VV, AA}) > 1500 \text{ GeV}. \quad (4)$$

Most other physically reasonable models will give bounds lying between these two.

Experiments at higher-energy $e^+e^-$ colliders will probe even deeper into the electron. Figure 2 shows $\Delta_{ee}$ at $\sqrt{s}=100$ GeV for the same four models. We chose $\Lambda$ in each case so that $|\Delta_{ee}|\simeq 5\%-8\%$ over a large angular range. Note the

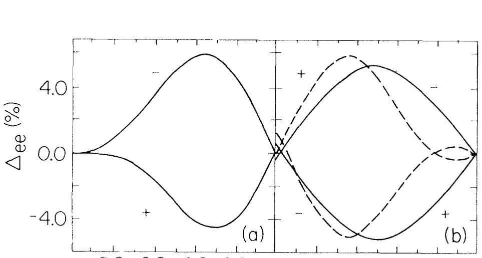


FIG. 1. $\Delta_{ee}(\cos\theta)$, in percent, at $\sqrt{s}=35$ GeV. (a) The LL and RR models with $\Lambda=750$ GeV. (b) The VV model (solid lines) with $\Lambda=1700$ GeV and the AA model (dashed lines) with $\Lambda=1400$ GeV. The ± signs refer to the overall sign of the contact interaction in each case.

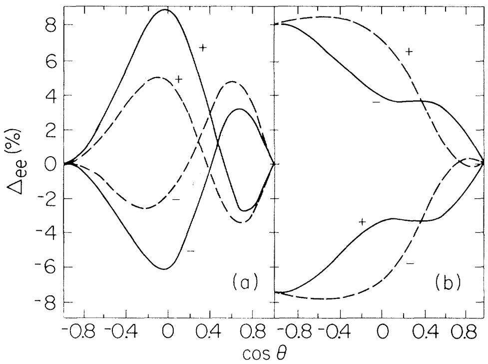


FIG. 2. $\Delta_{ee}(\cos\theta)$, in percent, at $\sqrt{s} = 100$ GeV. (a) The LL model (solid lines) and RR model (dashed lines) for $\Lambda = 2$ TeV. (b) The VV model (solid) and AA model (dashed) for $\Lambda = 5$ TeV. The $\pm$ signs have the same meaning as in Fig. 1.

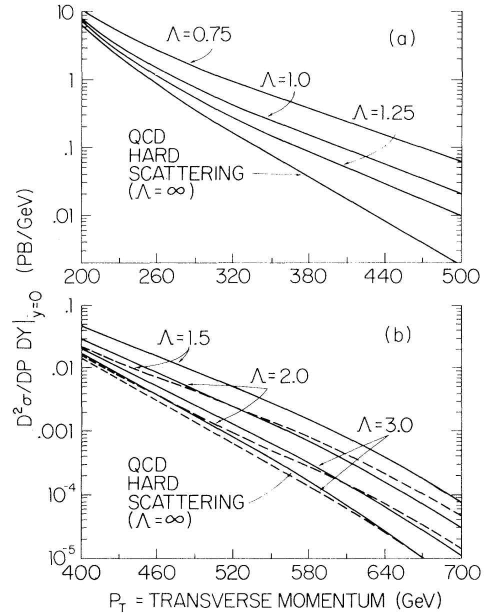


FIG. 3. The jet production cross section (in picobarns/gigaelectronvolt) at rapidity $y = 0$ vs transverse momentum at $\sqrt{s} = 2$ TeV in (a) $\bar{p}p$ collisions and (b) $pp$ collisions for various $\Lambda$ (in teraelectronvolts). The solid and dashed lines in (b) refer, respectively, to the plus and minus signs in Eq. (5). As a result of a cancellation near $y = 0$, the interference is negligible in (a).

distinctive effects of parity-nonconserving $Z^0$ terms. We expect that high-luminosity $Z^0$ factories will be able to set the limits $\Lambda(\mathrm{LL}, \mathrm{RR}) > 2$ TeV and $\Lambda(\mathrm{VV}, \mathrm{AA}) > 5$ TeV.[2,13]

*$\bar{q}q$ and $qq$ hard scattering.* The most general $SU(3) \otimes SU(2) \otimes U(1)$-invariant contact interaction involving only light quarks $q_{\mathrm{L,R}} = (u, d)_{\mathrm{L,R}}$ contains twelve independent helicity-conserving terms.[13] Here, we consider only the simple case of the product of two left-handed color- and isospin-singlet currents:

$$\mathcal{L}_{qq} = \pm(g^2/2\Lambda^2)\bar{q}_{\mathrm{L}}\gamma_\mu q_{\mathrm{L}}\bar{q}_{\mathrm{L}}\gamma^\mu q_{\mathrm{L}}. \quad (5)$$

We have calculated the cross section for high-$p_T$ jet production using lowest-order QCD and the interaction (5). The contributions of light quark and gluon jets were included. The results are shown in Fig. 3 for $\bar{p}p$ and $pp$ collisions at $\sqrt{s} = 2$ TeV. We assume that an effect is detectable if it gives a deviation from the expected QCD shape that is at least a factor of 2 and amounts to at least 100 events/yr. Then, for a $\bar{p}p$ collider with annual integrated luminosity of $10^{37}$ cm$^{-2}$, the limit $\Lambda > 1.0$ TeV can be set for the interaction (5). The corresponding limit for a $pp$ collider with $10^{40}$ cm$^{-2}$ is $\Lambda > 1.5$–$2.0$ TeV. More immediately, the CERN $\bar{p}p$ collider, with integrated luminosity $10^{36}$ cm$^{-2}$, can limit $\Lambda \gtrsim 250$ GeV for this interaction.

*$e^+e^- \to \mu^+\mu^-$.* If the electron and the muon have one or more constituents in common, the helicity-conserving terms in their contact interaction are

$$\mathcal{L}_{e\mu} = \frac{g^2}{\Lambda^2} \sum_{i,\, j=\mathrm{L,R}} \eta_{ij}{}' \bar{e}_i \gamma_\lambda e_i \bar{\mu}_j \gamma^\lambda \mu_j, \quad (6)$$

where $\Lambda$, $g^2$, and $\eta_{ij}{}'$ are normalized as in Eq. (1). The fractional deviation $\Delta_{e\mu}$ from the electroweak cross section for $e^+e^- \to \mu^+\mu^-$ has the following properties: (1) Existing measurements at $\sqrt{s} = 35$ GeV are consistent with $|\Delta_{e\mu}| \lesssim 6\%$–$8\%$ over a wide angular range.[5] This corresponds to $\Lambda > 1.4$ TeV for LL and RR models and to $\Lambda > 2.2$ TeV for VV and AA. These bounds on lepton substructure are stronger, but more model dependent, than those in Eq. (4). Muon decay and $\nu_\mu$-$e$ elastic scattering give $\Lambda \gtrsim 6$ TeV for a LL isovector interaction and $\Lambda \gtrsim 2$ TeV for a LL isoscalar interaction. (2) For $\sqrt{s} \ll \mu_z{}^2$, $\Delta_{e\mu}(\mathrm{LL}) \cong \Delta_{e\mu}(\mathrm{RR}) \propto (1 + \cos\theta)^2$. Also, $\Delta_{e\mu}(\mathrm{VV}) \cong$ const, while $\Delta_{e\mu}(\mathrm{AA}) \propto \cos\theta$; these effects could be hidden by a normalization error and by the $Z^0$-induced asymmetry, respectively. (3) Because $\gamma$ and $Z^0$ appear only in the $s$ channel, the beam energy can be tuned to enhance the effect of particular space-time structures in $\Delta_{e\mu}$. When $\mathrm{Re}(1 + g_i g_j s/e^2 s_z) = 0$, the $\eta_{ij}{}'$ contribution is negligible, $\sim s/\Lambda$,[4] while the fractional deviations due to other couplings are greater than at nearby energies. This occurs at $\sqrt{s}_{\mathrm{LL}} = 77.4$ GeV, $\sqrt{s}_{\mathrm{RR}} = 82.2$ GeV and $\sqrt{s}_{\mathrm{RL}} = 115.9$ GeV.

Finally, comparable limits on other flavor-nondiagonal interactions can be obtained from existing data on deep-inelastic $\nu_\mu$-nucleon scattering, $\bar{p}p \rightarrow \mu^+\mu^- X$ at $\sqrt{s} = 2$ TeV, and $e$-$p$ collisions at $Q^2 = (100 \text{ GeV})^2$.

We have shown that flavor-diagonal contact interactions induced by preon-binding forces significantly alter hard-scattering cross sections at energies well below $\Lambda$. Searches for these effects are the most sensitive model-independent tests of quark and lepton substructure. If $\Lambda \simeq 1$–5 TeV, deviations from the standard model will soon be observable. The coming generation of multi-teraelectronvolt colliders should be able to detect substructure up to $\Lambda \simeq 10$–50 TeV. But, if $\Lambda$ is only a few teraelectronvolts, the implications for experiments at these colliders will be more profound. In particular, if $\Lambda \simeq 2$ TeV, the Bhabha cross section at a 1 TeV×1 TeV linear $e^+e^-$ collider[2] would be $\sim 1/\Lambda^2 \simeq 0.1$ nb, or about 5000 units of $R$.

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[9]Only if $\psi$ is a Goldstone fermion of spontaneously broken global supersymmetry will its associated dimension-six interactions vanish. See W. Bardeen and V. Visnjić, Nucl. Phys. B194, 422 (1982).

[10]By implication, we assume that $G_F$ and $\sin^2\theta_W$ take the values determined from $\nu_\mu$-nucleon scattering by ignoring contact interactions. While this assumption is difficult to justify satisfactorily and models exist which violate it (see the last two papers in Ref. 7), it may soon be confirmed by the observation of $Z^0$ and $W^\pm$ in $\bar{p}p$ collisions.

[11]The existence of such relatively large interference terms of Bhabha scattering has been noted by John Preskill, Invited talk presented at the Conference on Novel Results in Particle Physics, Vanderbilt University, 1982 (unpublished).

[12]We use $\mu_z = 93.0$ GeV, $\Gamma_z = 2.92$ GeV, and $\sin^2\theta_W = 0.222$. See W. Marciano and A. Parsa, in *Proceedings of the Cornell $Z^0$ Theory Workshop, Ithaca, New York, 1981*, edited by M. E. Peskin and S.-H. H. Tye (Cornell Univ. Press, Ithaca, 1981), p. 127.

[13]This will be discussed in more detail by E. Eichten, H. Kagan, and K. Lane, to be published.