Comments and Addenda

The Comments and Addenda section is for short communications which are not of such urgency as to justify publication in **Physical Review Letters** *and are not appropriate for regular Articles. It includes only the following types of communications: (1) comments on papers previously published in* **The Physical Review** *or* **Physical Review Letters**; *(2) addenda to papers previously published in* **The Physical Review** *or* **Physical Review Letters**, *in which the additional information can be presented without the need for writing a complete article. Manuscripts intended for this section should be accompanied by a brief abstract for information-retrieval purposes. Accepted manuscripts will follow the same publication schedule as articles in this journal, and galleys will be sent to authors.*

Parity nonconservation in high-transverse-momentum collisions*

Ephraim Fischbach and George W. Look
Physics Department, Purdue University, West Lafayette, Indiana 47907
(Received 2 October 1975)

It is suggested that the suppression of strong-interaction cross sections at large transverse momenta could make possible the detection of parity-nonconserving weak effects in high-energy collisions. A parton-model calculation for $pp \rightarrow pX$ gives parity-nonconserving effects of the order of 10^{-3} which could be detectable by presently available techniques.

Recently attention has been drawn[1] to the possibility that the suppression of strong-interaction cross sections at large transverse momenta might make it possible for weak effects (such as nonvanishing longitudinal polarizations) to be seen in high-energy hadron-hadron scattering. This suggestion is motivated in part by the observation that strong-interaction differential cross sections have been measured down to $\approx 10^{-36}$ cm^2/sr, which is comparable to the differential cross sections characteristic of weak processes. To cite some typical results,

$$pp \rightarrow pp: \; d\sigma/d\Omega = 9\times 10^{-37} \text{ cm}^2/\text{sr} \quad (\text{Ref. } 2),$$

$$pW \rightarrow \pi^- X: \; E\frac{d\sigma}{d^3p} = (1.6 \pm 0.9)\times 10^{-38} \text{ cm}^2 c^3/\text{GeV}^2\,\text{sr} \quad (\text{Ref. } 3),$$

$$pp \rightarrow \pi^0 X: \; E\frac{d\sigma}{d^3p} = (2.99 \pm 2.16)\times 10^{-36} \text{ cm}^2 c^3/\text{GeV}^2\,\text{sr} \quad (\text{Ref. } 4),$$

which compare to $d\sigma(\nu_e e^- \rightarrow \nu_e e^-)/d\Omega = 1.3\times 10^{-38}$ cm^2/sr at $s = 10$ GeV^2 in the conventional $V-A$ theory. The possibility of detecting weak effects in hadronic processes is of particular interest at the present time in the light of recent experiments[5] which suggest that effects of the expected magnitude may in fact be observable. It is evident, however, that for any significant enhancement of the weak amplitude to be realized it is essential that qualitatively different mechanisms govern the strong and weak production processes. In particular, it is necessary that the weak amplitude have the property that it falls slowly, if at all, with transverse momentum. Depending on the view adopted, and the process in question, such a possibility may or may not seem realistic: On the one hand, weak production requires a mechanism that is necessarily different from that of the strong interaction since the weak interaction is very short-ranged and involves a net change of parity and/or strangeness. Thus, for example, the strong component in high-energy elastic proton-proton scattering can be diffractive whereas the weak parity-nonconserving (pnc) component cannot. On the other hand, our experience with high-energy scattering, be it strong, electromagnetic, or weak semileptonic, suggest that hadrons behave at high energies as assemblages of pointlike constituents, and are likely to fragment into these constituents in energetic collisions irrespective of the details of the scattering process. In this view the rapid falloff of strong cross sections at large transverse momenta is simply a statement about the properties of *hadronic matter* and as such may be insensitive to the details of the underlying interactions. The object of this note is to amplify on the preceding remarks in an attempt to answer the following question: Suppose that a significant enhancement of weak interaction effects is indeed seen at large transverse momentum. What would this teach us about the strong and/or weak scattering amplitudes? Since the falloff of the strong or weak amplitudes with transverse momentum is a highly model-dependent effect, we proceed to examine models of several characteristic processes in an effort to ascertain the circumstances under which a weak enhancement might be expected.

(1) $pp \to pp$. For proton-proton elastic scattering the differential cross section $d\sigma(s)/dt$ falls rapidly with t (or with the scattering angle θ), a fit to the data giving[6] ($\sqrt{s}$ = c.m. energy, $\sqrt{t}$ = momentum transfer)

$$d\sigma(s)/dt \propto s^{-9.7}(\sin\theta)^{-14}, \qquad (1)$$

for $s \gtrsim 15$ GeV^2 and $|t| > 2.5$ GeV^2. Constituent models of various types[7-9] have enjoyed some success in describing pp scattering and seem capable of reproducing the experimental results, at least qualitatively. For example, Gunion *et al.*[8] have deduced that $d\sigma/dt \propto s^{-12}(\sin\theta)^{-10.4}$ to be compared to Eq. (1). The common qualitative feature of such models is a picture of wide-angle scattering in which the rapid falloff of $d\sigma/dt$ with t is due to the tendency of hadrons to fragment in energetic collisions such as would produce particles with large transverse momenta. These models would then suggest that the weak-interaction-induced pnc $pp \to pp$ amplitude should also fall dramatically with θ although not necessarily at the same rate as for the strong interactions. If this is indeed the case, then no significant enhancement of the weak amplitude relative to the strong amplitude will be seen at large t above the value $\approx 10^{-6}$ expected at small t.[1] We note that although the above picture suggests a qualitative similarity of the parity-conserving (pc) and pnc amplitudes, some features, such as the s dependence, will likely differ owing to the fact that the weak coupling constant $G = 10^{-5}/m_p^2$ is not dimensionless.

Although no enhancement of the pnc amplitude is suggested by constituent models, the same may not hold true for other models of pp elastic scattering. In considering alternative models we exclude those which do not lend themselves to the introduction of pnc effects in a natural way. In this class we include various "geometric" descriptions of $pp \to pp$ in which the incident proton is pictured as being diffracted by the target proton. Among mechanisms capable of giving a significant pnc enhancement the most extreme would be those in which the protons behaved as partons and scattered without fragmenting at all. An illustrative (if naive) example of this is provided by a model in which the weak pp amplitude $\mathcal{T}$ is given by

$$\mathcal{T} = g^2[\bar{p}\gamma_\lambda(1+\gamma_5)p][\bar{p}\gamma_\mu(1+\gamma_5)p]W_{\lambda\mu}, \qquad (2)$$

where $W_{\lambda\mu} = (\delta_{\lambda\mu} + q_\lambda q_\mu/m_W^2)(q^2 + m_W^2)^{-1}$ is the propagator for a hypothetical W boson of mass $m_W \approx 37$ GeV, and $g^2/m_W^2 = G/\sqrt{2}$. From (2) we find that the longitudinal proton polarization $\mathcal{P}$ would already be near its maximum value, $\mathcal{P} = -1$, for $s = 59.7$ GeV^2 and $|t| = 20.4$ (GeV/c)^2 corresponding to the experimental situation in Ref. 2. However, inclusion of characteristic dipole form factors reduces the value of $\mathcal{P}$ to $\approx 10^{-6}$, thus suggesting that sizeable weak effects are not likely to be seen in elastic proton-proton scattering.

(2) $pp \to pX$: Inclusive pp scattering is of particular interest since it is experimentally the easiest process to study using an extension of the techniques of Ref. 5. We distinguish the following three possibilities (the second and third of which will later be shown to be negligible):

(a) X is a nonstrange hadronic state. In this case $pp \to pX$ can receive contributions from an interference between the strong interaction and the $\Delta S = 0$ weak interaction (for which we detect only the pnc contribution).

(b) X is a strange hadronic state. Now the production mechanism must be pure weak, and hence parity-nonconserving effects arise from the interference between the pnc and the pc nonleptonic weak amplitudes.

(c) X contains a lepton-neutrino pair. The production mechanism must again be pure weak. In inclusive reactions where X is not observed all three of the above mechanisms can contribute. It is, however, reasonable to expect that one of these mechanisms will dominate in a given kinematic situation and so we proceed to estimate their respective contributions. For case (a) we consider the parton model of Fig. 1 where the weak parton-parton interaction is given by Eq. (2) with $m_W = 37$ GeV. In the notation of Berman, Bjorken, and Kogut (BBK)[10] the invariant differential cross section for the weak scattering $p(p_a) + p(p_b) \to p(p_c) + X$ is given by $[s = -(p_a + p_b)^2]$

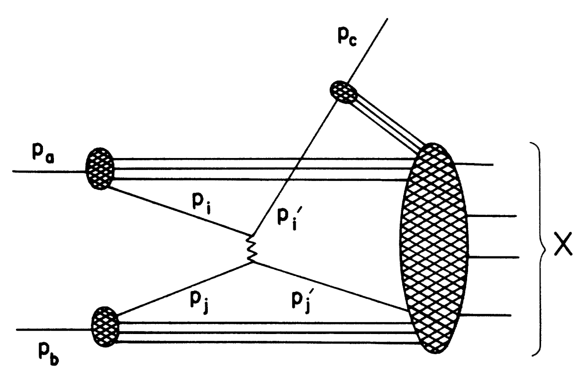

FIG. 1. Parton model for the weak process $p(p_a) + p(p_b) \to p(p_c) + X$. The wavy line denotes a weak vector boson of mass 37 GeV.

$$E_c\frac{d\sigma_w}{d^3p_c}=\frac{G^2}{2\pi^2}\int\left[\sum_i\frac{1}{e_i^{\,2}}F_i\left(\frac{x_2y_1}{y_1y_2-x_1}\right)\right]\left[\sum_j\frac{1}{e_j^{\,2}}F_j(y_1)\right]\frac{G(y_2)m_W^{\,4}dy_1dy_2}{(y_1y_2-x_1)(m_W^{\,2}y_2+y_1x_2s)^2}+(x_1\to x_2)\,, \tag{3}$$

where $x_1=-(p_b-p_c)^2/(p_a+p_b)^2$, $x_2=-(p_a-p_c)^2/(p_a+p_b)^2$, e_i is the charge of parton i, and F,G are the parton distribution functions defined by BBK. In writing (3) we have assumed for simplicity that all the partons are charged and interact with a common strength via either a charged-current or a neutral-current interaction. We thus tend to overestimate the cross section if interactions involving neutral currents are suppressed, but at the same time we underestimate the cross section if interactions involving neutral partons can take place. A detailed discussion of these points will be given elsewhere but for present purposes it suffices to note that modifications of the above model, such as exclusion of neutral-current interactions, produce relatively small changes in the magnitudes of the expected pnc effects. For $F_j(y_1)$ we have used the modified Kuti-Weisskopf functions[11,12] of Ref. 12, while for $G(y_2)$ we have used

$$G(y_2)=\kappa\sum_i F_i(y_2)=\kappa[\nu W_2(y_2)]\,, \tag{4}$$

where νW_2 is the proton structure function in deep-inelastic electron scattering, and κ is a proportionality constant which is evaluated as follows: Using energy conservation we find

$$\int_0^1 dy_2G(y_2)=1=p+K+\pi+\cdots\,, \tag{5}$$

where p, K, and π are the relative multiplicities[13] of protons, kaons, and pions respectively, $p:K:\pi\cong 2:3:5$, and where we have neglected all other contributions. When the proton contribution to Eq. (5), $p\cong\frac{1}{5}$, is combined with the known experimental value[12] of $\int dy_2\nu W(y_2)$ we find $\kappa\cong 1.15$. With the functions F and G specified, Eq. (3) can be numerically integrated and the results are given in Table I along with the experimental values of the corresponding strong differential cross sections.[3]

The polarization $\mathcal{P}$ of the outgoing proton is given in terms of the weak and strong amplitudes $\mathcal{T}_w$ and $\mathcal{T}_s$ by

$$\mathcal{P}=\frac{|\mathcal{T}_w^+ + \mathcal{T}_s^+|^2-|\mathcal{T}_w^- + \mathcal{T}_s^-|^2}{|\mathcal{T}_w^+ + \mathcal{T}_s^+|^2+|\mathcal{T}_w^- + \mathcal{T}_s^-|^2}\cong-\sqrt{2}\left(\frac{E_c d\sigma_w/d^3p_c}{E_c d\sigma_s/d^3p_c}\right)^{1/2}, \tag{6}$$

where $\mathcal{T}_w^{\pm}$ ($\mathcal{T}_s^{\pm}$) is the weak (strong) amplitude for producing a proton (with $E_c\cong|\vec{p}_c|$) in a state of $\pm$ helicity, and where we have assumed that $|\mathcal{T}_w^{\pm}| \ll |\mathcal{T}_s^{\pm}|$ as suggested by Table I. In the absence of a detailed theory of the distribution functions for polarized partons, we have also assumed that the same distribution function $G(y_2)$ describes the "decay" of both polarized and unpolarized partons into the final proton, and that the longitudinal parton polarization is transmitted undiminished to the proton.

TABLE I. Invariant cross sections and calculated parity-nonconserving parameters for $pp\to pX$ evaluated at $\theta_{\text{c.m.}}=90°$ ($x_1=x_2=p_\perp/\sqrt{s}=x_\perp/2$), and $\sqrt{s}=19.4$ GeV. $\mathcal{P}$ and $\mathcal{Q}$ are defined in Eqs. (6) and (7), respectively, and the experimental data are from Ref. 3. We have ignored the corrections arising from the fact that experimentally $\theta_{\text{c.m.}}\approx 77°$ rather than 90°, as these are small compared to other uncertainties in the calculation.

$x_\perp$	$E\frac{d\sigma^{\text{exp}}}{d^3p}\left(\frac{\text{cm}^2c^3}{\text{GeV}^2\text{sr}}\right)$	$E\frac{d\sigma_w}{d^3p}\left(\frac{\text{cm}^2c^3}{\text{GeV}^2\text{sr}}\right)$	$-\mathcal{P}$	$E\frac{d\sigma_w^+}{d^3p}\left(\frac{\text{cm}^2c^3}{\text{GeV}^2\text{sr}}\right)$	$E\frac{d\sigma_w^-}{d^3p}\left(\frac{\text{cm}^2c^3}{\text{GeV}^2\text{sr}}\right)$	$-\mathcal{Q}$
0.24	5.81×10^{-31}	7.65×10^{-40}	5.1×10^{-5}	4.89×10^{-40}	1.04×10^{-39}	1.3×10^{-5}
0.32	1.83×10^{-32}	1.29×10^{-40}	1.2×10^{-4}	8.02×10^{-41}	1.77×10^{-40}	3.2×10^{-5}
0.40	6.88×10^{-34}	2.08×10^{-41}	2.5×10^{-4}	1.27×10^{-41}	2.90×10^{-41}	6.9×10^{-5}
0.48	3.16×10^{-35}	3.00×10^{-42}	4.4×10^{-4}	1.79×10^{-42}	4.20×10^{-42}	1.3×10^{-4}
0.54	1.57×10^{-36}	6.13×10^{-43}	8.8×10^{-4}	3.61×10^{-43}	8.65×10^{-43}	2.6×10^{-4}
0.56	⋯	3.49×10^{-43}	⋯	2.05×10^{-43}	4.93×10^{-43}	⋯
0.62	1.0×10^{-37}	5.65×10^{-44}	1.1×10^{-3}	3.27×10^{-44}	8.02×10^{-44}	3.2×10^{-4}
0.64	⋯	2.92×10^{-44}	⋯	1.68×10^{-44}	4.15×10^{-44}	⋯
0.72	⋯	1.44×10^{-45}	⋯	8.13×10^{-46}	2.06×10^{-45}	⋯
0.80	⋯	2.83×10^{-47}	⋯	1.57×10^{-47}	4.09×10^{-47}	⋯
0.88	⋯	8.32×10^{-50}	⋯	4.53×10^{-50}	1.21×10^{-48}	⋯
0.96	⋯	3.79×10^{-55}	⋯	2.00×10^{-55}	5.58×10^{-55}	⋯

With respect to case (b) $\mathcal{P}$ must be of order $(d\sigma_w/d\sigma_s)$, since the strong interaction conserves strangeness, and hence this contribution to $\mathcal{P}$ can be neglected if we assume that the nonleptonic $\Delta S=0$ and $\Delta S=1$ weak amplitudes are comparable. We can similarly estimate the contribution to $\mathcal{P}$ when X contains a lepton pair [case (c)] by noting that in simple parton models the same suppression factors would enter here as would for the strong process $pp\to pX$. Hence no enhancement of the weak production relative to the strong would be expected. Since, in addition, $\mathcal{P}$ must again be of order $(d\sigma_w/d\sigma_s)$ this contribution to $\mathcal{P}$ can also be safely neglected. Thus the dominant contribution to $\mathcal{P}$ comes from the interference of the strong and $\Delta S=0$ weak nonleptonic amplitudes whose contributions are given in Table I. We see from the table that as the transverse momentum $p_\perp$ (or $x_\perp$) of the proton increases $|\mathcal{P}|$ also increases, indicating that the weak cross section is falling less rapidly with $p_\perp$ than is the strong cross section. This enhancement of $\mathcal{P}$ can be traced in the present case to the short range of the weak interaction: If the range is increased by decreasing m_W to ~1 GeV, then $|\mathcal{P}|$ decreases from 1.1×10^{-3} to 1.1×10^{-5} at $x_\perp=0.62$.

Parity nonconservation in inclusive pp scattering is also manifested through the asymmetry parameter $\mathcal{A}$,

$$\mathcal{A}=\frac{d\sigma^+-d\sigma^-}{d\sigma^++d\sigma^-}\cong\frac{(E_c\,d\sigma_w^+/d^3p_c)^{1/2}-(E_c\,d\sigma_w^-/d^3p_c)^{1/2}}{(E_c\,d\sigma_s/d^3p_c)^{1/2}} \tag{7}$$

where $d\sigma^\pm$ are the inclusive cross sections for scattering of a beam of incident protons with initial $\pm$ helicity, and where the subscripts s, w denote the strong and weak cross sections, respectively. The structure functions describing the decay of the initial polarized proton into partons are obtained from the modified Kuti-Weisskopf functions by appropriately constraining these functions in accordance with the Bjorken sum rule.[14] Tables I and II exhibit our results for $pp\to pX$ and $pp\to\pi X$, respectively, where in the latter case $G(y_2)$ is the function appropriate to pion production.[10] We note that $|\mathcal{A}|$ can be as large as $\sim10^{-4}$ under currently available experimental conditions. Since a value of this order could be detected by presently available techniques[15] our estimates suggest that parity nonconservation could be seen in high-transverse-momentum collisions. Should this indeed prove to be the case, the following information could be extracted from such experiments: (i) As s increases $|\mathcal{P}|$ and $|\mathcal{A}|$ will increase towards some maximum value. $|\mathcal{P}_{\max}|$, $|\mathcal{A}_{\max}|$, and the value(s)

TABLE II. Invariant cross sections and calculated values of the asymmetry parameter $\mathcal{A}$ for $pp\to\pi^+X$ defined in Eq. (7). The kinematics are the same as in Table I, and the experimental data are from Ref. 3.

$x_\perp$	$E\frac{d\sigma^{\rm exp}}{d^3p}\left(\frac{{\rm cm}^2c^3}{{\rm GeV}^2{\rm sr}}\right)$	$E\frac{d\sigma_w^+}{d^3p}\left(\frac{{\rm cm}^2c^3}{{\rm GeV}^2{\rm sr}}\right)$	$E\frac{d\sigma_w^-}{d^3p}\left(\frac{{\rm cm}^2c^3}{{\rm GeV}^2{\rm sr}}\right)$	$-\mathcal{A}$
0.08	1.64×10^{-27}	2.78×10^{-38}	5.32×10^{-38}	1.6×10^{-6}
0.12	2.48×10^{-28}	8.86×10^{-39}	1.73×10^{-38}	2.4×10^{-6}
0.16	3.52×10^{-29}	3.49×10^{-39}	6.95×10^{-39}	4.1×10^{-6}
0.24	1.02×10^{-30}	7.04×10^{-40}	1.46×10^{-39}	1.2×10^{-5}
0.32	3.22×10^{-32}	1.62×10^{-40}	3.48×10^{-40}	3.3×10^{-5}
0.40	1.60×10^{-33}	3.73×10^{-41}	8.27×10^{-41}	7.5×10^{-5}
0.48	7.52×10^{-35}	7.86×10^{-42}	1.80×10^{-41}	1.7×10^{-4}
0.54	4.25×10^{-36}	2.21×10^{-42}	5.17×10^{-42}	3.8×10^{-4}
0.56	...	1.41×10^{-42}	3.32×10^{-42}	...
0.62	3.5×10^{-37}	3.28×10^{-43}	7.89×10^{-43}	5.3×10^{-4}
0.64	...	1.93×10^{-43}	4.68×10^{-43}	...
0.72	...	1.72×10^{-44}	4.29×10^{-44}	...
0.80	...	7.24×10^{-46}	1.86×10^{-45}	...
0.88	...	6.40×10^{-48}	1.70×10^{-47}	...
0.96	...	2.81×10^{-52}	7.80×10^{-52}	...

of s at which these occur, could provide some information on m_W and on some other features of the weak interaction which have been accessible to date only through the study of parity-nonconserving effects in low-energy nuclear physics.[16] (ii) If, conversely, the weak interaction is assumed to be known (at least approximately), then a knowledge of the s dependence of $\mathcal{P}$ and $\mathcal{A}$ can be used as a probe of the strong interaction. Such an approach may be useful in practice if one could isolate from both the weak and strong cross sections their common dependence on the structure functions F and G leaving the weak and strong parton-parton scattering amplitudes themselves to be compared.

The authors wish to thank D. Hitlin and U. Nauenberg for calling this problem to their attention, and H. Frauenfelder, J. Gunion, F. Low, J. Missimer, L. Wolfenstein, and C. N. Yang for valuable discussions concerning various experimental and theoretical aspects of this problem. We also wish to collectively thank our many other colleagues for their suggestions and encouragement during the course of this work.

---

*Work supported in part by the U. S. Energy Research and Development Administration.

[1]E. M. Henley and F. R. Krejs, Phys. Rev. D 11, 605 (1975).
[2]G. Cocconi *et al*., Phys. Rev. 138, B165 (1965).
[3]J. W. Cronin *et al*., Phys. Rev. Lett. 31, 1426 (1973); Phys. Rev. D 11, 3105 (1975).
[4]F. W. Büsser *et al*., Phys. Lett. 46B, 471 (1973).
[5]J. M. Potter *et al*., Phys. Rev. Lett. 33, 1307 (1974); J. D. Bowman *et al*., *ibid*. 34, 1184 (1975).
[6]P. V. Landshoff and J. C. Polkinghorne, Phys. Lett. 44B, 293 (1973).
[7]T. T. Wu and C. N. Yang, Phys. Rev. 137, B708 (1965). These authors elaborate the view that the falloff of the elastic *pp* differential cross section at large transverse momentum should be independent of the excitation process. We thank Professor Yang for an instructive discussion on this point.
[8]J. F. Gunion, S. J. Brodsky, and R. Blankenbecler, Phys. Rev. D 8, 287 (1973).
[9]T. T. Chou and C. N. Yang, Phys. Rev. 175, 1832 (1968); Phys. Rev. Lett. 20, 1213 (1968).
[10]S. M. Berman, J. D. Bjorken, and J. B. Kogut, Phys. Rev. D 4, 3388 (1971).
[11]J. Kuti and V. F. Weisskopf, Phys. Rev. D 4, 3418 (1971).
[12]R. McElhaney and S. F. Tuan, Phys. Rev. D 8, 2267 (1973); Nucl. Phys. B72, 487 (1974).
[13]S. D. Ellis and M. B. Kislinger, Phys. Rev. D 9, 2027 (1974).
[14]R. P. Feynman, *Photon-Hadron Interactions* (Benjamin, Reading, Mass., 1972) p. 158.
[15]H. Frauenfelder, private communication.
[16]E. Fischbach and D. Tadić, Phys. Rep. 6C, 123 (1973).