cident neutrino. A nonzero value again implies T nonconservation.

It should be emphasized again that these tests depend directly on the assumption that the reaction amplitude (S-matrix element) is the matrix element of H_w, which is Hermitian. In very-high-energy neutrino interactions, the appearance of these apparently T-nonconserving terms could, instead, be a signal that the weak interactions are no longer weak enough to be treated only in lowest order.

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[13]See Kabir, Ref. 10, Appendix C, p. 113 ff.

Copious Direct Photon Production: A Possible Resolution of the Prompt-Lepton Puzzle*

Glennys R. Farrar† and Steven C. Frautschi
California Institute of Technology, Pasadena, California 91125
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We propose that all direct leptons not due to vector meson decay can be attributed to the decay of virtual photons. At $p_\perp \approx 3$ GeV/c, we expect γ/π, the ratio of direct photons to pions, to be about 10 to 20% for $\sqrt{s} \approx 20$-60 GeV.

The copious production of prompt leptons in hadronic collisions[1-6] has thus far evaded a satisfactory explanation. The problem has been to explain simultaneously the large value of l/π, roughly 10^{-4}, the lack of any threshold or low-$p_\perp$ turnover, at least for electrons, and the apparent equality of the e/π and μ/π ratios. If there were sizable production at large $p_\perp$ of low-invariant-mass virtual photons, which internally converted to lepton pairs, the large l/π ratio and its lack of structure could be explained.[7] At first sight, however, there are two problems with such an explanation: The γ/π ratio required at large $p_\perp$, $\sim 10^{-1}$, seems too large, and e/π should be considerably larger than μ/π, contrary to experimental evidence.[2]

In what follows we present a picture of large-$p_\perp$ bremsstrahlung where, in fact, the γ/π ratio naturally becomes as large as 10^{-1} at large $p_\perp$. In this picture e/μ is really ≈ 2 or 3, the apparent equality of e/π and μ/π being explained as an artifact of the interpretation of the experiments. That is, the large-$p_\perp$ experiments reporting $e/\pi \simeq 1\times 10^{-4}$ have not measured the "true" e/π ratio, since they either overestimated the π^0 spectrum by assuming that there are no η's or direct γ's,[2] or they rejected the low-mass pairs which are responsible for making e/π larger than μ/π.[3] We also show that the low-$p_\perp$ data are qualitatively consistent with this picture.

Now we describe our picture in more detail. At low c.m. momentum, γ/π is surely of order α. However, if it is true that short-distance quark-gluon dynamics becomes important as the momentum transfer increases, we expect γ/π to increase with $p_\perp$ because of the weakening of the strong interactions relative to electromagnetism. Furthermore, dimensional-counting arguments[8] imply that the cross section for large-$p_\perp$ pion production should fall faster by one power of s that that for γ production at fixed x and $\theta_{\mathrm{c.m.}}$, i.e., at 90°, $\gamma/\pi \sim sf(x_\perp)$. Thus there are two short-distance effects, both of which result in large γ/π at large $p_\perp$ and $\sqrt{s}$.[9]

The large-$p_\perp$ single-lepton spectrum at 90° is to a good approximation

$$\frac{E\,d\sigma}{d^3p}=\frac{\alpha}{2\pi E}\int_{(2m)^2}^{Q_{\max}^2}\frac{dQ^2}{Q^2}\left(1+\frac{2m^2}{Q^2}\right)\int_{E+Q^2/4E}^{\infty}dQ_0\,\frac{Q_0\,d\sigma}{d^3Q}, \tag{1}$$

where $Q_0 d\sigma/d^3Q$ is the spectrum for inclusive virtual-photon production which we could compute in a detailed model of large-$p_\perp$ dynamics. In the absence of such a model all we know (from dimensional scaling[8]) is that $Q_0 d\sigma/d^3Q = bsf(Q_\perp/\sqrt{s}, Q^2/s, \theta)E\,d\sigma/d^3p_\pi$. We make the guess that the virtual-photon spectrum is obtained from the large-$p_\perp$ pion spectrum by replacing $p_\perp$ of the pion by Q_0 of the photon, and multiplying by $\beta \equiv \gamma/\pi = bsf(Q_0/\sqrt{s})$.[10] The function f is not determined theoretically.

While for comparison with experiment we use the actual pion spectrum to determine $Q_0 d\sigma/d^3Q$, it is useful for orientation to study the simple case corresponding to a pion spectrum $p_\perp^{-n}$ and $\beta(Q_0,s)\equiv\gamma/\pi = bQ_0^{\,r}s^{1-r/2}$. The integrals can now be done analytically, yielding at 90° and high $p_\perp$

$$l/\pi = [\alpha\beta(p_\perp,s)/2\pi(n-1-r)][\ln(p_\perp/2m_l)^2 - c_n], \tag{2}$$

where c_n is about 1 for $n\approx 8$. Two interesting qualitative features are evident from Eq. (2). The e/π ratio should be 2–3 times the μ/π ratio. Furthermore, since the actual π spectrum has an effective n which increases as $p_\perp$ increases, any increase with $p_\perp$ of $\beta(p_\perp,s)$ is at least partially offset by the increase of $n-1-r$ in the denominator.

Now we turn our attention to the data, using Eq. (1). Taking into account the result of Bourquin and Gaillard[11] that vector mesons contribute about 0.3×10^{-4} to l/π, we find that, for example, $\beta = 0.0014Q_0\sqrt{s}$ GeV^{-2} or $\beta = 0.004Q_0^{3/2}s^{1/4}$ GeV^{-2} give good agreement with the μ/π data[1] at $\sqrt{s} = 23.4$ (see Fig. 1). We then obtain the predictions for e/π at $\sqrt{s}=23.4$ and 52.7 shown in Fig. 1. They have an inherent theoretical uncertainty of about 30%,[10] and in addition are sensitive to the size of the vector meson contribution to μ/π since that affects the overall normalization of β.

In order to compare with the e/π experiments of Refs. 2 and 3 we must consider how those measurements were made. Büsser *et al.*[3] measuring $(e^+ + e^-)/(\pi^+ + \pi^-)$ reject low-invariant-mass pairs experimentally by requiring a pulse in the scintillation hodoscope of between 0.5 and 1.5 times minimum ionization. Given the spectrum of pairs, the effect of their cuts on the single-lepton spectrum can be calculated, and amounts to dividing the non-vector-meson part of the "true" spectrum by 2.1. Correcting for this gives the corresponding "true" e/π ratio shown in Fig. 1. The agreement with the predictions of the model, especially for $\beta = 0.0039Q_0^{3/2}s^{1/4}$, is not bad. Furthermore, the spectrum of dilepton masses (see Fig. 2) predicted by our model is below the upper limit set by Büsser *et al.*, even in the range of their greatest sensitivity, $(Q^2)^{1/2}$ between 200 and 400 MeV.

The Columbia University–Fermilab experiment[2] measures the ratio of direct electrons to those coming from the external conversion of photons. They thus report the ratio $e/``\pi^0" = e_{\text{tot}}/``\pi^0" - D``\pi^0"/``\pi^0" = (1.0\pm0.2)\times10^{-4}$ where "π^0" is the spectrum the pions would have if every photon came from a π^0 decay, e_{tot} is the total electron spectrum, and $D``\pi^0"$ is the correction for Dalitz decays.[12] There are two reasons why "π^0" overestimates π^0. First of all, η's decay 38% of

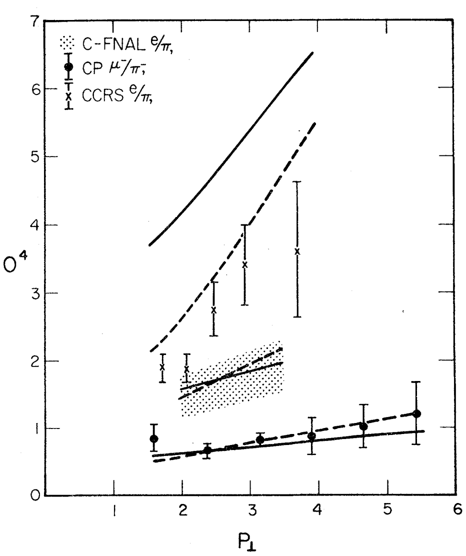

FIG. 1. Data on μ/π and e/π, treated as described in the text. "C-FNAL" refers to Ref. 2, "CP" to Ref. 1, and "CCRS" to Ref. 3. Dashed and solid lines are, respectively, predictions corresponding to $\beta = 0.004\times p_\perp^{3/2}s^{1/4}/\text{GeV}^2$ and $\beta = 0.0014p_\perp\sqrt{s}/\text{GeV}^2$ for (from the bottom up) μ/π (23.4 GeV), e/π (23.4 GeV), and e/π (52.7 GeV).

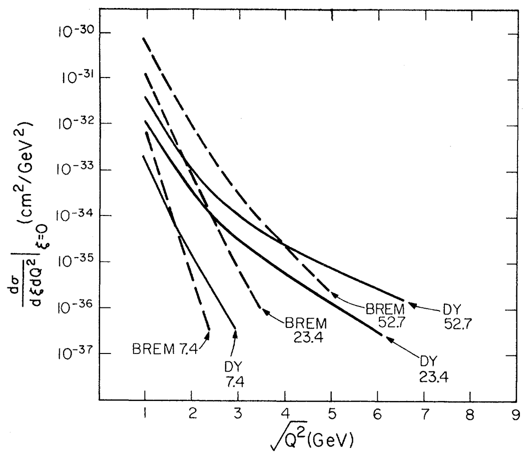

FIG. 2. The cross section for pair production at 90° $[d\sigma(pp\rightarrow l^+l^-X)/d\xi\, dQ^2$ with $\xi \equiv 2Q_{\parallel}/\sqrt{s}=0]$, plotted against the invariant mass $\sqrt{Q^2}$. The curves give a typical bremsstrahlung (BREM) prediction of this paper with the specific choice $\beta = 0.004 p_\perp^{3/2} s^{1/4}/\mathrm{GeV}^2$, and the Drell-Yan (DY) prediction of Ref. 18, at $\sqrt{s}=7.4$, 23.4, and 52.7 GeV.

the time into 2γ's and it is known that $\eta^0/\pi^0=\frac{1}{2}$,[13] whereas in the analysis of their experiment they assumed $\eta^0/\pi^0=0$. Secondly, the directly produced photons should not be counted as coming from pion decay. This is a large effect, since the photons coming from π decays are reduced in magnitude relative to π's at the same $p_\perp$ by the "parent-child factor"[14] which is of order $\frac{1}{5}$. Using the γ spectra above we obtain the "true" e/π ratios corresponding to their result (shown in Fig. 1 as the shaded region) which is consistent with our predictions.

An experiment[6] at Serpukhov at 90°, $1.8<p_\perp<2.3$, $p_{\mathrm{lab}}=35$, 50, and 70 GeV/c is qualitatively in agreement with our expectations: It shows a decrease in μ/π with decreasing $\sqrt{s}$ at constant $p_\perp$. Detailed comparison cannot be made without an analysis of the vector meson contribution and knowledge of the pion spectrum itself. The experiment of Bintinger *et al.*[4] is also consistent with this model.

Summarizing up to this point, we have shown that at $p_\perp \gtrsim 2$ GeV/c, vector mesons and bremsstrahlung photons which are copiously produced relative to pions can account for the single-electron and -muon experiments at Fermilab and the CERN intersecting storage rings. In fact, the data seem to be consistent with $\gamma/\pi \sim s f(x_\perp)$ as expected on dimensional-counting grounds.[8] Within the factor of two uncertainties emphasized above,[10] our fit to the muons gives a prediction for the spectrum of direct, real photons: $\gamma/\pi \sim 0.004 p_\perp^{3/2} s^{1/4}$. Numerically, at $\sqrt{s}=23.4$ GeV, γ/π ranges from about 5% at $p_\perp=2$ to about 15% at $p_\perp=4$, and of course increases as $s^{1/4}$ for fixed $p_\perp$.

In order to be compelling, the same mechanism should be capable of accounting for the direct leptons at low $p_\perp$ as well. While we cannot theoretically predict the detailed behavior of γ/π, we note that the behavior of γ/π required to account for observed l/π ratios is not unreasonable, in that it decreases from $\sim 10^{-1}$ at large $p_\perp$ to $\sim 10^{-2}$ at low $p_\perp$. The experiments[5,6] at $p_\perp=0$ and $x_{\parallel}>0.1$ find μ^-/π^- on the order of $(\frac{1}{5}-1)\times 10^{-4}$ and decreasing with $x_{\parallel}$. We have computed the forward lepton spectrum from

$$Q_0\, d\sigma/d^3Q \sim \exp(-15.4 Q_{\parallel}/\sqrt{s})\exp\{-6[(Q_\perp^2+Q^2)^{1/2}-(Q^2)^{1/2}]\},$$

mimicking the $p_\perp$ and $x_{\parallel}$ dependence of hadron production. We find that with $\gamma/\pi=10^{-2}$, $\mu^-/\pi^-(x_{\parallel}=0.1)=3.1\times 10^{-5}$ and $\mu^-/\pi^-(x_{\parallel}=0.5)=1.5\times 10^{-5}$. The vector mesons, assuming $\rho=\omega=\frac{1}{5}\pi^-$, give a contribution about a third that size. Thus with $\gamma/\pi \simeq 1.5\times 10^{-4}$ we get good agreement with the μ/π result of Leipuner *et al.*[5] Our conclusion is that the magnitude and shape of the μ spectrum at $p_\perp=0$, $x_{\parallel}>0.1$ is reasonable in the context of a bremsstrahlung mechanism. A consequence of the bremsstrahlung component which could be used to test for its presence is the large e/μ ratio in this kinematic regime: $e/\mu(x_{\parallel}=0.1)=6$ and $e/\mu(x_{\parallel}=0.5)=3$.

A recent experiment[15] at 30° in the c.m. system, $\sqrt{s}=53$ GeV, reports that as $p_\perp$ is decreased from 1.4 to 0.2 GeV/c, the e/π ratio increases from 1.3×10^{-4} to 6×10^{-4}. In our model a constant value of $\beta \approx 3\%$ at $p_\perp \lesssim 1.2$ GeV/c gives that behavior (essentially because the exponential spectrum at low $p_\perp$ gives a child/parent ratio $\sim 1/p_\perp$). Thus a qualitatively consistent picture of the entire kinematic regime emerges: β is large for large $p_\perp$, decreases as $p_\perp^{3/2}$ for decreasing $p_\perp$, and levels off at a fairly constant value of a few percent for $p_\perp \lesssim 1$ GeV/c.[16]

In summary, in this Letter we make the phenomenological proposition that direct leptons are the result of vector-meson decay and of the internal conversion of a bremsstrahlung spectrum of virtual photons. In order to get agreement with the lepton data we require $\gamma/\pi \sim 10^{-1}$ at large $p_\perp$. We give theoretical arguments for why γ/π should be large at high $p_\perp$, and emphasize the importance of the behavior of γ/π for illuminating the dynamics of large-$p_\perp$ hadron production.[9] Going into more detail, we show that the dimensional-counting prediction $\gamma/\pi \sim s f(p_\perp/\sqrt{s})$ is consistent with present data. There is no evidence against such copious γ production, since absolute normalizations between experiments on $(\pi^+ + \pi^-)/2$, π^0 deduced from the single-γ spectrum, and π^0 reconstructed from two γ's are not adequate to rule out discrepancies of $\approx 50\%$. In fact, there is actually one experiment[17] on $\gamma p \to (\gamma, \pi) + X$ which has reported a γ/π ratio which is increasing with $p_\perp$ and is bigger than 10%.

Whether this picture is correct or not can be determined by checking the following specific predictions: (1) The 90° dilepton spectrum should behave as $\beta Q^{-2} E\, d\sigma(pp \to \pi X) d^3p$, with $p_\perp$ of the π replaced by some function of Q^2 and $Q_\perp{}^2$ such as Q_0. For dileptons of large $Q_\perp$, $d\sigma/dQ^2 \sim 1/Q^2$ when Q^2 is small compared to $Q_\perp{}^2$. A typical spectrum (assuming $p_\perp \to Q_0$) of large-invariant-mass pairs at 90°, integrated over $Q_\perp$, is shown in Fig. 2 in comparison with that predicted by a Drell-Yan model.[18] (2) The rest of the final state in events in which a single lepton is seen should look very much as it does when a hadron of the same $p_\perp$ is seen.[19] Consequently e-h correlations should resemble h-h correlations. (3) Direct γ/π production at large $p_\perp$ should be of the order of 10^{-1}, not only in $pp \to (\pi^0, \gamma) + X$ but also in $\pi^\pm p \to (\pi^0, \gamma) + X$, $\gamma p \to (\pi^0, \gamma) + X$,[17] $ep \to e + (\pi^0, \gamma) + X$, and in $e^+e^- \to (\pi^0, \gamma) + X$ at large x.

We are indebted to the CERN-Columbia-Rockefeller-Saclay collaboration,[3] and especially to B. G. Pope, for their help and cooperation in comparing our predictions to their measurements.

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[7]This mechanism has been discussed by C. O. Escobar, Cambridge University Report No. DAMTP 75/9 (to be published); Ming Duong-van, SLAC Report No. SLAC-PUB-1604 (to be published); and J. D. Bjorken and H. Weisberg, SLAC Report No. SLAC-PUB-1631 (to be published).

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[9]Both these arguments would be inapplicable if the underlying mechanism for large-$p_\perp$ processes were $qq \to qq$ followed by scale-invariant fragmentation of a quark. However, since $E\,d\sigma/d^3p$ for large-$p_\perp$ hadron production does not dominantly behave as $p_\perp{}^{-4} f(x_\perp)$ as suggested by that picutre, nature may in fact rely on far-off-shell quarks (i.e, short distances) in creating large-$p_\perp$ hadrons; in that case our arguments about γ/π should be correct.

[10]This procedure amounts to guessing the dependence of $Q_0\, d\sigma/d^3Q$ on Q^2, guided by studying Feynman diagrams. However, it is by no means unique. We have checked the sensitivity of our results to alternate Q^2 dependence [e.g., $p_\perp \to (Q_\perp{}^2 + Q^2/4)^{1/2}$] as well as to the Q^2 dependence of the turn-on of longitudinal polarization. Depending on those details the value of γ/π required to account for the single leptons may vary by a factor of two; however, the shape and magnitude of the lepton spectra are rather insensitive, varying by $\approx 30\%$, once β is determined by requiring agreement with the observed μ/π ratio at some $p_\perp$ and $\sqrt{s}$, say 2.5 GeV/c and 23.4 GeV.

[11]M. Bourquin and J. M. Gaillard, to be published.

[12]D is only very weakly dependent on the ratio η^0/π^0. Ref. 2 finds $D = (1.6 + 0.8\eta^0/\pi^0)/(1.0 + 0.38\eta^0/\pi^0) \times 10^{-4}$.

[13]A. M. Eisner *et al.*, Phys. Rev. Lett. 33, 865 (1974); F. W. Büsser *et al.*, Phys. Lett. 55B, 232 (1975).

[14]By way of illustration, if the pion spectrum were $Ap_\perp{}^{-n}$ then the spectrum of the decay photons would be $2(n-1)^{-1} A p^{-n}$. Since n is large, this is not so much greater than the direct photon spectrum $\beta A p_\perp{}^{-n}$ even if β is only $\frac{1}{10}$. The total overestimate is then "π^0" $= \pi^0\,[1 + 0.38(\eta^0/\pi^0) + \beta(n-1)/2]$. Reference 2 in fact reports that "π^0" $\approx$ all negatives, which implies "π^0" $\approx 1.4(\pi^+ + \pi^-)/2$.

[15]L. Baum *et al.*, to be published.

[16]The Penn-Stony Brook experiment [E. W. Beier *et al.*, in *Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Stanford, California, 1975,* edited by W. T. Kirk (Stanford Linear Accelerator Center, Stanford, Calif., 1975)] on e^+/π^- at $0.8 \lesssim p_\perp \lesssim 1.5$ and $p_{\rm lab} = 10, 15$, and 24 GeV/c is complex to evaluate, depending as it does on the details of their low-mass pair rejection. However, the result $\gamma/\pi \approx 10^{-4}$ could be in accord with the competition between the low-$p_\perp$ e/π enhancement and the slow decrease with s of γ/π.

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[18]G. R. Farrar, Nucl. Phys. B77, 429 (1974).

[19]This similarity of final states is observed by the CERN-Columbia-Rockefeller-Saclay group as cited in Ref. 6.