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DIRECT LEPTON PRODUCTION AND THE DRELL-YAN MECHANISM

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ERRATUM

Reference 5 in this paper should be changed to read:

5. E. W. Beier <u>et al</u>., Paper B-05, Submitted to the International Conference on High Energy Physics, Palermo, June 1975, and to be published.

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ABSTRACT

We suggest that the Drell-Yan mechanism, when applied to low-mass dilepton production, underestimates the yield by a factor ~ 25 because it neglects the contribution coming from annihilation of produced parton-antiparton pairs. If this is correct, the observed direct-lepton production may be accounted for by electromagnetic production of low-mass dileptons possessing high total transverse momentum.

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Considerable evidence exists¹⁻⁶ that, despite some indications to the contrary⁷⁻¹¹ the direct lepton production observed in hadron collisions satisfies the following properties:¹²

- i) At least at $\theta_{CM} \sim 90^{\circ}$, $e/\pi \approx \mu/\pi \sim 10^{-4}$, independent of $p_1(1-1.5 < p_1 < 6 \text{ GeV})$, of atomic number of the target, and of 's $(5 \leq \sqrt{s} \leq 60 \text{ GeV})$.
- ii) In the forward direction, the mass spectrum of directly produced dimuons peaks at low values, less than 1 GeV.
- iii) Decays of vector mesons ρ , ω , φ into lepton pairs

cannot account for even half the observed yield.

This strongly suggests that the origin of the dileptons is electromagnetic: a virtual photon is produced in the collision which then converts (internally) into a lepton pair. This may either be via bremsstrahlung of a virtual photon from some charged constituent present during the collision, or via annihilation of such a constituent with its antiparticle. However, both mechanisms have their difficulties. Biemsstrahlung mechanisms have in general no way of suppressing real photon emission, as well as virtual photons. And the relationship between real and virtual emission is governed by the usual Kroll-Wada type of factor for internal conversion. Experimentally the required amount of internal conversion is not present, as determined in the experiments of CCR-Saclay³ and Penn-Stony Brook,⁵ which reject leptons that are members of low-mass pairs. Furthermore, the bremsstrahlung mechanism implies a dilepton mass distribution $dN/dm \sim 1/m$ for small This leads to the number of leptons produced being proportional m. to $\log m_{max}/m_{\ell}$. The e/μ ratio would then be

~ $(\log m_{max}/m_{e})/(\log m_{max}/m_{\mu})$, and for $m_{max} \lesssim 1$ Gev one should have $e/\mu \gtrsim \log 10^{3}/\log 10 = 3$, quite inconsistent with the observations. Therefore, at least for $\theta_{CM} \sim 90^{\circ}$, bremsstrahlung mechanisms don't easily explain the data.

This leaves the annihilation of constituents as the leading candidate for an electromagnetic mechanism. Provided the effective mass or mean momenta of the constituents exceed the muon mass (an eminently reasonable assumption) the minimum virtual photon mass will exceed 2m,, and there is no problem with the e/μ ratio. The problem is only of rate. Annihilation calculations have generally used the Drell-Yan parton-antiparton annihilation mechanism, 13 and the results have been a lepton inclusive spectrum with the wrong p, dependence, as well as a total dilepton yield much too small. However, the emphasis in the theoretical considerations has been production of massive lepton pairs. It has been recognized for a long time, and especially by Landshoff and Polkinghorne, 14 that the Drell-Yan formula needs to be corrected when the dilepton mass is small. The problem is how to estimate the modification and to ascertain that the observed dilepton yield is "reasonable".¹⁵ This is the purpose here. Our strategy is to first estimate from the inclusive lepton spectra the total dilepton production cross section (per unit rapidity) do/dy. Having determined the experimental yield, we then estimate $d\sigma/dy$ from theory, first from an unmodified Drell-Yan formula, and then with a modification which takes into account the presence of the many wee partons and antipartons produced in the collision process and which may reannihilate into leptons before the products of the

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This brings theory and experiment within reach of each other for $d\sigma/dy$.

If this mechanism is in fact correct, it implies that the bulk of the high p_{\perp} inclusive lepton yield is made up of low-mass dileptons produced at high total transverse momentum.

'I. Estimate of Total Dilepton Production

At large p_{\perp} , the e^{-}/π^{-} ratio is, within 20-30%, 10^{-4} . At large s, and $\theta_{CM} = 90^{\circ}$, the integrated yield of π^{-} is, for pp collisions, and per unit of rapidity

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}y}\right)_{\pi^{-}} \approx 2 \times 10^{-26} \mathrm{cm}^2$$
 (1)

We assume $e^{-}/\pi^{-} \leq 10^{-4}$ for all p_{\perp} , and thus

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}y}\right)_{\mathrm{direct e}} \leq 2 \times 10^{-30} \mathrm{cm}^2 \ . \tag{2}$$

However, for $p_{\perp} < 1 \text{ GeV}$, the e^{-}/π^{-} ratio may well decrease; if the minimum dilepton mass is of order M perhaps

$$\left(\frac{d\sigma}{dy}\right)_{\text{direct e}} \approx e^{-b\sqrt{p_{\perp}^2 + M^2}}$$
 (3)

With such a parametrization, one obtains upon integration over p,

$$\left\langle \frac{\mathrm{e}^{-1}}{\pi^{-1}} \right\rangle \approx 10^{-4} (1 + \mathrm{bM}) \mathrm{e}^{-\mathrm{bM}}$$
 (4)

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$$\frac{e^{-}}{\pi^{-}} \approx 10^{-4} \left[\frac{e^{-6} \sqrt{p_{\perp}^{2} + M^{2}}}{e^{-6p_{\perp}}} \right] \approx 10^{-4} e^{-3M^{2}/p_{\perp}} .$$
 (5)

Thus we should have $M \le 0.5$ GeV. With M = 0.5 GeV, we get $\langle e^{-}/\pi^{-} \rangle \sim 2 \times 10^{-5}$; hence

$$4 \times 10^{-31} \text{cm}^2 \lesssim \left(\frac{\text{d}\sigma}{\text{d}y}\right)_{e^+e^-} < 2 \times 10^{-30} \text{cm}^2 .$$
 (6)

II. Drell-Yan Calculation

The standard Drell-Yan formula for production of a dilepton of (large) mass Q and longitudinal momentum P is, at very high cms energy \sqrt{s} ,

$$\frac{d\sigma}{dQ^{2}dP} = \left(\frac{1}{3}\right)^{2} \int \frac{dx_{1}}{x_{2}} \int \frac{dx_{2}}{x_{2}} \sum_{i=\frac{p}{p}, \overline{n}, \lambda} e_{i}^{2} f_{i}(x_{1}) \overline{f}_{i}(x_{2})$$

$$\cdot \frac{4\pi\alpha^{2}}{3Q^{2}} \delta(Q^{2} - x_{1}x_{2}s) \delta\left[P - \frac{\sqrt{s}}{2}(x_{1} - x_{2})\right].$$
(7)

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Here x_1 and x_2 are longitudinal fractions of the incident partons i, e_i are their charges, and f_i is the density of parton of type i in rapidity space. The sum is over both partons and antipartons. The factor $\left(\frac{1}{5}\right)^2$ accounts for the possibility of color:

The normalization of f_{i} is such that for electroproduction

$$v W_2 = \sum_{i=p,n,\lambda} e_i^2 [f_i(x) + \overline{f}_i(x)] .$$
 (8)

For $v W_2 \sim 1/3$ and $f_i = \overline{f}_i$ for small x, we get

$$\nu W_{2} = \left(\frac{h}{9} + \frac{1}{9} + \frac{1}{9}\right) \times 2 < f > \approx \frac{1}{5}$$

$$< f > \sim \frac{1}{h} \quad .$$
(9)

or

Reduction of the Drell-Yan formula gives for large s, and for the dilepton produced in the central region $(x_1, x_2 < < 1)$

$$\frac{d\sigma}{dQ^{2}dy} = \left(\frac{1}{3}\right)^{2} \frac{4}{3} \frac{\pi\alpha^{2}}{q^{4}} \cdot \left(\frac{4}{9} + \frac{1}{9} + \frac{1}{9}\right) \cdot 2 < f^{2} .$$
 (10)

Putting in the numbers, including $< f > \sim 1/4$ gives

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}y}\right) \sim \left(\frac{1}{3}\right)^{?} \left(\frac{\mathrm{l} \mathrm{GeV}^{2}}{\mathrm{Q}_{\mathrm{min}}^{2}}\right) \cdot (7 \times \mathrm{l0}^{-33} \mathrm{cm}^{2}) .$$
 (11)

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Probably 0.1 GeV² \lesssim (Q²)_{min} \lesssim 0.5 GeV². Hence

$$\left(\frac{1}{3}\right)^{?}(1.4 \times 10^{-32} \text{cm}^{2}) < \left(\frac{\text{d}\sigma}{\text{d}y}\right)_{\text{Drell-Yan}} < \left(\frac{1}{3}\right)^{?}(7 \times 10^{-32} \text{cm}^{2}) . \tag{12}$$

Even ignoring the factor 3 from color, this estimate is a factor ~ 30 too small to account for the observation.

However, the unmodified Drell-Yan calculations is most likely an underestimate. It assumes a quark density $\left\langle \frac{dN_i}{dy} \right\rangle \simeq <f > \sim 1/4$ (per parton type) during the collision. This may be acceptable for leading partons, or for the density as measured by a lepton probe. However,

during the hadron-hadron collision, partons and antipartons are <u>pro-</u> <u>duced</u>: this is a certainty because we observe the produced hadrons which also must contain partons. We can in fact estimate the number of produced partons from the number of emerging pions. With $\frac{dN_{\pi}}{dy} \sim 2.5$, we have $\frac{dN_q}{dy} \sim \frac{dN_q}{dy} \geq 2.5$ and $\frac{dN_p}{dy} \approx \frac{dN_n}{dy} = \langle f \rangle \geq \frac{5}{4}$. Therefore $\langle f \rangle_{enhanced} = \frac{5}{4} = 5 \langle f \rangle_0$. With the cross section proportional to $\langle f \rangle^2$, we obtain a very crude estimate of an enhancement by a factor ~ 25 relative to the straight Drell-Yan formula.

$$\left(\frac{1}{\overline{3}}\right)^{?}(3.5 \times 10^{-31} \text{cm}^{2}) \lesssim \left(\frac{d\sigma}{dy}\right)_{\text{Drell-Yan}} \lesssim \left(\frac{1}{\overline{3}}\right)^{?}(2 \times 10^{-30} \text{cm}^{2}) .$$
 (13)

This is at worst a factor 3 away from the observations.¹⁶ Therefore, the parton-annihilation mechanism becomes a quite credible interpretation. Additional enhancement factors can be envisaged, including final state interactions (which increases the time in which the annihilating partons are in proximity) or perhaps clustering of the partons into proto-hadrons which have integral charge and thus a large annihilation probability. But it is hard to estimate any numbers from such loose talk.

It is likewise hard to deduce theoretically the p_{\perp} dependence of the inclusive lepton yield from these crude ideas. The only argument in support of constancy with p_{\perp} of the ℓ/π ratio is that the formation of a low-mass dilepton of given p_{\perp} and the formation of a meson with the same p_{\perp} both depend on very similar joint momentum distributions of the partons, and therefore may vary with p_{\perp} in a similar way. This is in contrast with the usual Drell-Yan calculations

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where the single-lepton p_{\perp} dependence comes out to be too flat,¹⁷ yielding a ℓ/π ratio that grows with p_{\perp} in disagreement with experiment. In these usual calculations the initial partons' transverse momenta are neglected and the single-lepton p_{\perp} dependence is simply a power law reflecting the power-law distribution of dilepton mass, which in turn depends only on the longitudinal momentum distribution of the incident partons.

III. Consequences

Of first importance is to determine whether the inclusive direct lepton production is of electromagnetic origin. The tests are obvious:

- i) The leptons must come in pairs.
- ii) For a given total momentum of a pair, the angular distribution in the pair rest frame must be consistent with the decay of a spin-one virtual photon (i.e., nearly isotropic).

We also expect a dilepton mass distribution $d\sigma/dQ$ roughly independent of dilepton total momentum, and peaked at small mass (probably below the ρ).¹⁸ For a while $d\sigma/dQ$ should fall faster than Q^{-3} (the Drell-Yan estimate) but eventually should take that form (at sufficiently high s, and for dileptons in the central plateau in rapidity).

At some level, bremsstrahlung of slightly virtual photons should also exist, with a mass spectrum $d\sigma/dQ \sim Q^{-1}$, extending all the way to threshold (~ 1 MeV for e⁻, ~ 200 MeV for μ^{-}). However, at least at large cms angles, this does not seem to be a dominant mechanism, as evidenced by the e/μ ratio of ~ unity.

One of us (J.D.B.) thanks F. Gilman and Minh Duong-van for helpful discussions.

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FOOTNOTES AND REFERENCES

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13.	S. D. Drell and T. M. Yan, Phys. Rev. Letters 25, 316 (1970).
<u>1</u> 4.	P. V. Landshoff and J. C. Polkinghorne, Nucl. Physics B33, 221
ù	(1971).
цĵ.	A new study, with emphasis on the low-mass dilepton production, has
	also been made by Minh Duong-van (private communication). He ob-
	tains a reasonable p_{\downarrow} distribution.
16.	Note that if $(q^2)_{min}$ is small (so that the upper limit of the
	estimate is attained) we expect that the characteristic mass M
	cutting off the lepton inclusive spectrum should likewise be
	small. This gives the upper limit of the experimental bound on

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 $d\sigma/dy$ as the most reasonable estimate. Therefore, there is considerably less than a factor 5 uncertainty in the comparisons of theory and experiment. That is, it seems not reasonable to compare the largest theoretical estimate with the smallest estimate of the experimental yield.

- 17. G. R. Farrar, Nucl. Phys. <u>B77</u>, 429 (1974).
- 18. A crude estimate of the mean dilepton mass at low p₁ is attainable from the assumption that the four-momentum of a parton is half that of a produced wee meson. Then

 $\langle m_{\ell\bar{\ell}}^2 \rangle \gtrsim \frac{1}{4} \langle (p_{\pi^+} + p_{\pi^-})^2 \rangle$ $\sim \frac{1}{2} \langle p_{\pi^+} \rangle \cdot \langle p_{\pi^-} \rangle$ $\sim \frac{1}{2} < E_{\pi} >^2$ $\sim \frac{1}{2} \cdot \frac{3}{2} \langle \mathbf{p}_{\perp \pi} \rangle^2$ ~ 0.08 Gev²

which gives $<m_{\ell\ell}>\gtrsim 280$ MeV.