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IMPLICATIONS OF THE RECENT $e^+e^- \rightarrow \text{hadron} + X$
DATA ON THE LEPTONIC WORLD

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A B S T R A C T

Trying to understand the recent " e^+e^- annihilation to hadrons" data, from a phenomenological point of view, we come to the conclusion that leptons should exhibit at very high energies (very small distances, of order 10^{-16} cm) interactions other than electromagnetic or weak, presumably of a hadronic nature. Consequences of such a behaviour are investigated.

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Despite the fact that the parton model explains fairly well the electro-production and neutrino production data ¹⁾, it seems to be in grave trouble with the new data from CEA and SPEAR ²⁾, concerning the e^+e^- annihilation to hadrons.

It is well known ³⁾ that the conventional parton model gives the following predictions (see the Figure) :

$$\sigma_{tot}(e^+e^- \rightarrow \text{hadrons}) \propto \frac{1}{s} \quad (1)$$

And, in $e^+e^- \rightarrow h(p) + \text{anything}$:

$$(a) \quad s \frac{d\sigma}{dx} = 2\pi\alpha^2 x \left[2\bar{W}_1 + \frac{x}{3}(\nu\bar{W}_2) \right] \equiv F(x) \quad (1')$$

$$(b) \quad \frac{d\sigma}{dP_T^2} = A(s) + B(s) P_T^2 \quad (1'')$$

$$\left(x \equiv \frac{E_{hadr.}}{E_{beam}} = \frac{2\nu.M}{s} \right)$$

where (1') and (1'') are derived by calculating the diagram :

Now, by just looking at the new data from CEA and SPEAR, we see that the above predictions are not satisfied.

In this note ^{*}), triggered by the recent data, we will try first (inspired by hadron physics), to understand them from a phenomenological point of view. Then we shall try to understand the consequences and implications of this analysis in other processes, and also its further implications in the world of leptons.

For the inclusive process $e^+e^- \rightarrow hX$ we define, as usual, the three independent variables :

$$s = (p_+ + p_-)^2, \quad t = (p_- - p)^2, \quad u = (p_+ - p)^2$$

and also the missing mass : $M^2 = (p_+ + p_- - p)^2$ related to them by :

*) A preliminary draft of the present work had been circulated in January 74. The present form of this note contains some modifications, after we came across Ref. 6).

$$s+t+u = M^2$$

(neglecting the hadron mass; we will be consistently doing this).

For the inclusive cross-section, using the generalized optical theorem ⁴⁾, we have :

$$E \frac{d^3\sigma}{dp^3} \propto \frac{1}{s} \text{Disc}_{M^2} \left[\begin{array}{c} e^+ \rightarrow e^+ \\ h \leftarrow h \\ e^- \rightarrow e^- \end{array} \right]_{\text{Forward}} \quad (3)$$

where the right-hand side of (3) represents the discontinuity in missing mass of the $3 \rightarrow 3$ forward amplitude $e^+e^-h \rightarrow e^+e^-h$. When t and u are large ($s \rightarrow \infty$, x small) one may expect a substantial contribution to (2) from a diagram like :

$$\begin{array}{c} e^+ \rightarrow e^+ \\ h \leftarrow h \\ e^- \rightarrow e^- \end{array} \quad (2')$$

where the blobs may be thought of as representing a kind of "diffractive" interaction - a sort of "Pomeron" exchange. (See below for possible explanations of the dynamical origin of this "Pomeron".) Now applying the usual (hadronic) inclusive phenomenology, we get :

$$E \frac{d^3\sigma}{dp^3} \propto \frac{1}{s} \text{Disc}_{M^2} \left[\begin{array}{c} e^+ \rightarrow e^+ \\ h \leftarrow h \\ e^- \rightarrow e^- \end{array} \right]_{\text{Forward}} = \frac{1}{s} \beta(m_T^2) |u|^{\alpha(0)} |t|^{\alpha(0)} \quad (4)$$

with $\alpha(0)=1$ (diffraction). Equation (4) is just the double $O(2,1)$ expansion ⁴⁾ of the forward $e^+e^-h \rightarrow e^+e^-h$ amplitude for all s, t, u large but $ut/s \simeq m_T^2$ finite. From (4) we get :

$$\frac{d^2\sigma}{dx dP_T^2} = \frac{\pi m_T^2 \beta(m_T^2)}{\sqrt{x^2 + \frac{4m_T^2}{s}}} \quad (5)$$

Scaling

or

$$\frac{d^2\sigma}{d(\cos\theta) dP_T^2} = \frac{\pi m_T^2 \beta(m_T^2)}{s \sin^2\theta} \quad (5')$$

Assuming that the central vertex (Pomeron-hadron) $m_T^2 \beta(m_T^2)$ falls rapidly with p_T (e.g., $\sim e^{-\lambda p_T}$, as in hadron physics), we may integrate p_T from zero to infinity, to get :

$$\frac{d\sigma}{dx} \propto \frac{1}{x} \quad (6)$$

or

$$\frac{d\sigma}{p dp} \propto \frac{1}{p^2}$$

(omitting the $4m_T^2/s$ term) and

$$\frac{d\sigma}{d(\cos\theta)} \propto \frac{1}{\sin^2\theta}$$

Predictions (6) seem to be consistent with the recent data in $e^+e^- \rightarrow h+X$, for small x (or, equivalently, small $\cos\theta$). So, a "two-component" picture ⁵⁾ in which diffraction [diagram (2')] dominates for small x , while the parton model [diagram (2)] takes up at large x , may be capable of explaining all of $e^+e^- \rightarrow$ hadrons data. When these data become available, we intend, in a subsequent paper, to present a quantitative fit along the above lines.

Now, if the above analysis is sensible, we may ask, why we do not see this diffractive interaction in the processes :

- i) $e^+e^- \rightarrow e^+e^-$
- ii) $e^+e^- \rightarrow \mu^+\mu^-$
- iii) $eN \rightarrow eN$ (or X)
- iv) $e^+e^- \rightarrow e^+e^-(\mu^+\mu^-) + \text{hadrons}$.

It has been checked ⁶⁾, that at present energies, the diffractive component is negligible as compared with the usual one (Q.E.D.), but at much higher energies, it will also play a fundamental role [for a thorough analysis, see Ref. 6)]. We also want to stress at this point that, because of the smallness of the cross-section for iv), as compared with that for $e^+e^- \rightarrow \text{hadrons}$,

$$\left(\sigma[e^+e^- \rightarrow e^+e^- (\mu^+\mu^-) + \text{hadrons}] < 10^{-5} \frac{S}{M_p^2} \sigma[e^+e^- \rightarrow \text{hadrons}] \right) \text{ for } S \leq 10^4 \text{ GeV}^2$$

when we write $e^+e^- \rightarrow h+X$ we can safely assume that X consists of hadrons only ⁷⁾.

We will now try to give some possible explanations of the origin of the "diffractive" interaction; what we have in mind, is the following: recently, it has been discovered ⁸⁾ that in the framework of a renormalizable Yang-Mills field theory with spontaneous breakdown, the vector bosons lie on Regge trajectories. If this Reggeization applies to unified theories of weak and electromagnetic interactions alone, then the slopes of the Regge trajectories of the W mesons and leptons would be of the order of $\sim (e^2/M_W^2) \simeq 10^{-5} M_p^{-2} \sim G_F$. If the reggeized W trajectory is linear, $\alpha_W(s) = \alpha_W(0) + G_F s$, then $\alpha_W(0) = 1 - e^2/k$ [$G_F = (e^2/kM_W^2)$, $k \sim 10$], which is very close to 1, and so contributes an almost constant term to cross-sections. Quite independently, there have been done some explicit calculations ⁹⁾, along these lines, showing that the photon may reggeize, and has a unit intercept ^{*}). If then we adopt some presently "accepted" ideas ¹⁰⁾, conserving the relation between the structure of a particle and the slope of the trajectory on which it lies, we reach the conclusion that the leptons have a composite nature characterized by a length $G_F^{-1/2}$. Then, we have a constant cross-section $2\pi G_F$ associated with the lepton-lepton diffractive scattering. [It is amusing to notice that $2\pi G_F \simeq 20 \text{ nb} \sim \sigma(e^+e^- \rightarrow \text{hadrons})$ which is consistent with the results in Refs. 2).] We want also to mention that many of the presently proposed models of unified weak and electromagnetic interactions contain heavy leptons. This means that probably we have not seen, yet, the whole spectrum of leptons (which may be as rich as the hadronic one), and surprises may be awaiting us at higher energies. If then we accept the fundamental philosophy that matter is the same in both hadrons and leptons, it does

*) Adding tower graphs, one gets an amplitude behaving like :

$$i(lgs)^{-2.5} 1 + \frac{11g^2 n}{32}$$

so here the "reggeized photon" is a fixed pole with intercept slightly greater than unit [see, H. Cheng and T.T. Wu, Proceedings of the International Symposium on Electron and Photon Interactions at High Energies, (Cornell 71), pp. 152-153].

not seem too unreasonable to accept that leptons, at very high energies (very small distances ^{*}) have non-Q.E.D. interactions (presumably of the same kind as the hadrons have). We come to the conclusion that all elementary particles have the same kind of interactions, but the appearance or not of an interaction at a certain energy, depends on the ratio of the energy we are talking about over the inverse of the fundamental length associated with the interaction. (Here $G_{\text{P}^0}^{\frac{1}{2}}$)

We have to stress, at this point, that the hadronic and leptonic diffractive mechanisms ($\mathbb{P}$ and $\mathbb{P}'$ respectively) cannot be the same at the same energies. Because, assuming factorization, we have for small x :

$$\begin{array}{c}
 \begin{array}{c}
 \text{P} \rightarrow \text{P} \\
 \pi \leftarrow \pi \\
 \text{P} \rightarrow \text{P}
 \end{array}
 \begin{array}{c}
 \text{P} \\
 \text{P}
 \end{array}
 \end{array}
 = E \frac{d^3 \sigma^{\text{P}}}{dp^3} = \sigma_{\text{PP}}^{\infty} \beta(\pi, \mathbb{P}) = f(x, p_T, s)$$

$$\begin{array}{c}
 \text{e}^+ \rightarrow \text{e}^+ \\
 \pi \leftarrow \pi \\
 \text{e}^- \rightarrow \text{e}^-
 \end{array}
 \begin{array}{c}
 \mathbb{P}' \\
 \mathbb{P}'
 \end{array}
 = E \frac{d^3 \sigma^{\text{e}}}{dp^3} = \sigma_{\text{ete}^-}^{\infty} \beta(\pi, \mathbb{P}')$$

Note that the central vertices are independent of the slopes of $\mathbb{P}$ and $\mathbb{P}'$ since they are taken at zero momentum transfer. Looking at $pp \rightarrow \pi X$ data ¹¹⁾ for $0.1 < x < 0.3$, we have:

$$0.4 < \frac{\pi \sqrt{s}}{2E} < \beta(\pi, \mathbb{P}) > \equiv \frac{1}{\sigma_{\text{PP}}^{\infty}} \frac{d\sigma^{\text{P}}}{dx} = \frac{\pi}{x} \cdot \frac{1}{\sigma_{\text{PP}}^{\infty}} f(x, p_T, s) < 8 \quad (7)$$

On the hand, looking at the error associated with recent measurements ¹²⁾ of the $e^+e^- \rightarrow e^+e^-$ elastic total cross-section, we estimate $\sigma_{\text{el}}^{\infty}(e^+e^- \rightarrow e^+e^-) < 0.5 \text{ nb} \equiv \sigma_0$, so looking at the values of $d\sigma^{\text{e}}/dx$ for $0.1 < x < 0.3$ we get ^{**)}

*) We mean that this non-leptonic interaction occurs at lengths of order of 10^{-16} cm or smaller. Notice that we do not have any conflict with Q.E.D., which, presently, is valid up to distances of 5×10^{-15} cm.

**) Using $\text{Tel} = i\sigma_{\text{ete}^-}^{\infty} (s/s_0)^{\alpha' t}$, we get:

$$[\sigma_{\text{ete}^-}^{\infty}]^2 = 32\pi \log\left(\frac{s}{s_0}\right) \alpha' \sigma_{\text{elast}}^{\infty}(e^+e^- \rightarrow e^+e^-)$$

$$\frac{\eta\sqrt{s}}{2E} \langle \beta(\eta, P') \rangle \equiv \frac{1}{6_{e^+e^-}^\infty} \frac{d\sigma^e}{dX} < \frac{350 \text{ nb}}{25 \sqrt{\alpha'} \sigma_0} \quad (8)$$

where α' is the slope of P' . Now if (7) and (8) are to be equal, we need $\alpha' < 0.65 \times 10^{-2} \text{ GeV}^{-2}$; this bound is consistent with $\alpha' = G_F$, as we have suggested above, and it demonstrates the fact that the two Pomerons are not the same.

The smallness of α' is presumably related to the observation of Gervais, Neveu and Scherk ¹³⁾, that the zero slope limit of certain dual models gives an S matrix which, when evaluated in the tree graph approximation, is identical to the Born approximation computed from a Yang-Mills Lagrangian.

Very recently ¹⁴⁾, a gauge model of strong, electromagnetic and weak interactions has been put forward, exhibiting some of the features mentioned above, and where "the asymmetric response of leptons and baryons to strong interactions at presently attained energies would then be interpreted as a 'low' energy phenomenon".

In conclusion, we propose that in e^+e^- annihilation to hadrons, we begin to see some new interaction of leptons, perhaps "strong" interaction, at a tiny radius of the order of 10^{-16} cm .

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FIGURE CAPTION

The one-photon approximation to e^+e^- annihilation to
hadrons.

FIG.1