PHYSICAL REVIEW D VOLUME 13, NUMBER 11 1 JUNE 1976

Direct lepton production in the generalized vector-dominance model*

E. N. Argyres,† A. P. Contogouris, and C. S. Lam
Department of Physics, McGill University, Montreal, Canada

(Received 17 November 1975)

The direct production of leptons at large transverse momenta is studied in the generalized vector-meson-dominance model (GVDM). It is concluded that the known vector mesons (old and new) together with their GVDM partners may account for all the observed leptons.

The transverse-momentum (p_T) distribution of directly produced leptons in proton-proton collisions is known to parallel closely that of the pions, but at a level 10^{-4} smaller.[1] This naturally suggests that leptonic and hadronic production processes have a common origin. One particularly attractive model in this direction is to assume that the observed leptons come from the decay of vector mesons.

Of the familiar vector mesons, ϕ is known to be produced in pp collisions at a rate smaller than 5–10% (probably depending on p_T) of that of π,[2] thus not contributing significantly to lepton production[1]; in the present paper we ignore this contribution. The ψ meson, on the other hand, appears to contribute approximately $\frac{1}{3}$ of the leptonic rate (see below). The contributions of ρ and ω are not too well known from experiments, but are generally believed to be insufficient to account for the remaining leptonic rate.[1] However, excited states of these vector mesons, like the $\rho'(1600)$, have now been found, and they are expected to contribute, as well, to the calculated leptonic rate. More generally, assuming that lepton production proceeds via $pp\to\gamma+X$ with $\gamma\to l^+l^-$, it is difficult to accept that leptons are produced only when the 4-momentum Q of γ is near $Q^2=m_\rho^2$, m_ω^2, m_ϕ^2, or m_ψ^2; we expect that other values of Q^2 ($>m_\phi^2$ and $\neq m_\psi^2$) will also contribute to lepton production.

The purpose of this paper is to discuss the amount of such contributions in a generalized vector-dominance model (GVDM). GVDM has been applied successfully to (i) deep-inelastic lepton-hadron scattering, in which the scaling phenomena can be explained[3], (ii) electron-positron annihilation, where the hadron-to-muon cross-section ratio R is predicted to be 2.5 and 4.1, respectively, below and above the ψ threshold[4], and (iii) to explain the missing amount in the Compton sum rule.[3] More recently, in connection with deep-inelastic lepton-nucleon scattering, the phenomena that the usual quark-parton model attributes to the presence of the core (wee) partons are instead described by GVDM, and this predicts the core antiquark distribution in good agreement with the results of neutrino experiments.[5]

To obtain these results it is usually assumed[3] that the lepton pair decay branching ratio B_n of the vector meson V_n of mass M_n varies as M_n^{-2}, and that for the ρ and ω series of V_n's the mass squared M_n^2 satisfies

$$M_n^2=M_0^2(1+2n) \tag{1}$$

($M_0=m_\rho$ or m_ω). These assumptions together with the knowledge of the branching ratios for ρ and ω allow us to calculate the leptonic production rate in GVDM, once the cross sections for V_n production are known.

For the present calculation of the leptonic distribution at 90° c.m. angle, we assume the invariant inclusive differential cross section for producing a vector meson of mass M_n to be

$$E\frac{d\sigma_n}{d^3p}=c\frac{M_n}{(M_n^2+p_T^2)^4}\left[1-\frac{2(p_T^2+M_n^2)^{1/2}}{\sqrt{s}}\right]^9, \tag{2}$$

where $\sqrt{s}$ is the total c.m. energy. The justification of this form will now be discussed.

(a) p_T dependence. For fixed M_n and large p_T this form is equivalent to $p_T^{-8}(1-2p_T/\sqrt{s})^9$, which is the form suggested by the counting rules.[6,7] The factor $2p_T/\sqrt{s}$ has been replaced by $2(p_T^2+M_n^2)^{1/2}/\sqrt{s}$, so that the second factor in (2) may vanish at the edge of the phase space. When we move away from the edge of the phase space and go to the small p_T, we assume that the p_T^{-8} dependence should be replaced by $(p_T^2+M_n^2)^{-4}$, so that, just as in the second factor, all the p_T dependence comes through the energy factor $E_n=(p_T^2+M_n^2)^{1/2}$. Such assumptions are known to be correct in pp and e^+e^- single-particle inclusive distributions in the central region.[8] The distributions of $\pi, K, \bar{p}$ in these experiments are known to have very different slopes in p_T, but their distributions in the energy variable $(p_T^2+M^2)^{1/2}$ (M = mass of observed hadron) are very similar. We are here assuming that whatever mechanism

gives rise to this behavior for π, K, and $\bar{p}$ would also do for ρ, ω, and their excited states. In connection with this notice that a p_T distribution of the form $\sim(p_T^2+m_\rho^2)^{-4}$ accounts reasonably well for all available ρ-production data even at small p_T (<1 GeV).[9-11]

(b) M_n dependence. It is known that the muon-pair mass distribution in pp collisions goes down approximately like[7]

$$\frac{d\sigma_{\mu\mu}}{dM} \propto M^{-6}. \tag{3}$$

In addition to the M_n factor contained in E_n, the extra M_n factor in Eq. (2) is introduced there in order to satisfy Eq. (3). This can be seen as follows:

Notice first that as n increases $E\,d\sigma_n/d^3p$ decreases fast; also the branching ratio $B_n \sim M_n^{-2}$ decreases; thus only the first few vector mesons ($n \lesssim 4$) contribute significantly to lepton production. Then for $s \gg M_n^2$ Eq. (2) gives

$$\begin{aligned}\sigma(pp\to V_nX) &\sim B_n\int_0^{\sqrt{s}/2} dp_T^2 E\frac{d\sigma_n}{d^3p}\\ &\sim M_n^{-7}.\end{aligned} \tag{4}$$

On the other hand, Eq. (3) gives for the contribution of the vector meson at $M\approx M_n$

$$\sigma(pp\to \underset{\searrow\mu^+\mu^-}{V_n}X) \propto \int_{M_n-\Delta M_n/2}^{M_n+\Delta M_n/2} (d\sigma_{\mu\mu}/dM)dM \propto M_n^{-6}\Delta M_n\,. \tag{5}$$

From Eq. (1)

$$M_n\Delta M_n = M_0^2\Delta n\,, \tag{6}$$

so that with $\Delta n=1$ we have $\Delta M_n \propto M_n^{-1}$. This shows the consistency of Eqs. (2) and (3).

To fix the normalization constant c of Eq. (2) we shall assume that at large p_T the inclusive cross sections for ρ and ω production equal that for pion production. First, in connection with ρ, this assumption is suggested by recent data on $\pi^+p\to\rho X$ versus $\pi^+p\to\pi^-X$ at $p_T=1.0$–1.4 GeV and $s=30$–40 GeV^2;[10,11] also, some data on $pp\to\rho^0X$ in the central region at $p_T\simeq 1$ GeV and $s\simeq 45$ GeV^2 indicate that it is comparable to $\pi^+p\to\rho^0X$.[10] Notice that the ratio

$$r(\pi^+) \equiv \frac{d\sigma}{dp_T^2}(\pi^+p\to\rho^0X)\Big/\frac{d\sigma}{dp_T^2}(\pi^+p\to\pi^-X)$$

increases almost linearly with p_T^2 throughout $p_T=0$–1.4 GeV,[10,11] so that it is quite possible that at $p_T=3$–4 GeV $r(\pi^+)$ and $r(p)$ exceed unity; unfortunately at this moment there are no data on ρ production at $p_T>1.4$. Second, in connection with ω production, data at 12 and 24 GeV on the semi-inclusive reactions $pp\to\binom{\rho^0}{\omega}+$ charged particles give the same total cross sections.[12] Anyway,

$$E\frac{d\sigma}{d^3p}(pp\to\omega X)\simeq E\frac{d\sigma}{d^3p}(pp\to\rho^0X)$$

appears to be a popular working assumption.[7]

In the subsequent calculations we take

$$c = 8.68 \text{ mb GeV}^5\,.$$

In the approximation of neglecting the lepton mass the inclusive cross section $\omega\,d\sigma/d^3k$ for $pp\to l^\pm X$ is given in terms of the inclusive cross section $E\,d\sigma_n/d^3p$ for $pp\to V_nX$ and the branching ratio B_n by the sum[13]

$$\omega\frac{d\sigma}{d^3k} = \sum_n \frac{B_n}{2\pi}\int\frac{d^3p}{E}E\frac{d\sigma_n}{d^3p}(p,s)\delta(p\cdot k-\tfrac{1}{2}M_n^2)\,, \tag{7}$$

where p is the 4-momentum of the vector meson V_n. By eliminating the δ function we obtain

$$\omega\frac{d\sigma}{d^3k} = \sum_n\frac{B_n}{2\pi k}\int_{E_0}^{\sqrt{s}/2} dE\int_0^{2\pi} d\phi\, E\frac{d\sigma_n}{d^3p}(p,s)\,, \tag{8}$$

where

$$E_0 = k + M_n^2/4k\,, \tag{9}$$

and ϕ is the azimuthal angle that defines the direction of $\vec{p}$ in the plane perpendicular to the observed lepton.[13]

We have already noticed that $B_nE\,d\sigma_n/d^3p$ decreases fast with n so that only the first few values of n contribute significantly. Moreover, we are interested in the production of leptons (at 90° in the c.m. of colliding protons) with large (transverse) momentum k (> GeV). Then for $M_0=m_\rho$ or $M_0=m_\omega$ for the first few values of n we generally have $M_n^2 \ll k^2$. In this case $E\,d\sigma_n/d^3p$ is almost independent of ϕ (see Ref. 13) and the ϕ integration in Eq. (8) becomes trivial. Thus we use

$$\omega\frac{d\sigma}{d^3k} \simeq \sum_n\frac{B_n}{k}\int_{E_0}^{\sqrt{s}/2} dE\, E\frac{d\sigma_n}{d^3p}(p_T, s)\,. \tag{10}$$

The branching ratios are determined from

$$B_n = B_0M_0^2/M_n^2,$$

with $B_\rho = 5.5\times10^{-5}$ and $B_\omega = 7.5\times10^{-5}$.[14] The resulting inclusive lepton cross sections are given in Table I (for $\sqrt{s}=23.8$ and 52.7 GeV). For comparison the same table includes the contributions from ρ and ω alone; we see that depending on p_T and s, inclusion of the higher vector mesons increases the contributions by factors of 1.5–3.

At large transverse momenta ($k>2$ GeV) an important source for lepton production is the newly

TABLE I. The contributions of the various vector mesons to the inclusive lepton production cross section $\omega d\sigma/d^3k$ in cm^2/GeV^2.

k_T (GeV)	ρ	$\sum_n \rho_n$	ω	$\sum_n \omega_n$	$\sum_n \rho_n + \sum_n \omega_n + \psi$
			$\sqrt{s} = 23.8$ GeV		
2	0.216×10^{-34}	0.336×10^{-34}	0.294×10^{-34}	0.460×10^{-34}	1.8×10^{-34}
3	0.33×10^{-36}	0.677×10^{-36}	0.449×10^{-36}	0.923×10^{-36}	0.46×10^{-35}
4	0.103×10^{-37}	0.255×10^{-37}	0.14×10^{-37}	0.348×10^{-37}	1.2×10^{-37}
5	0.444×10^{-39}	0.125×10^{-38}	0.606×10^{-39}	0.173×10^{-38}	5×10^{-39}
			$\sqrt{s} = 52.7$ GeV		
2	0.674×10^{-34}	1.133×10^{-34}	0.979×10^{-34}	1.545×10^{-34}	6.678×10^{-34}
3	0.197×10^{-35}	0.46×10^{-35}	0.269×10^{-35}	0.627×10^{-35}	2.787×10^{-35}
4	0.132×10^{-36}	0.389×10^{-36}	0.181×10^{-36}	0.53×10^{-36}	1.85×10^{-36}

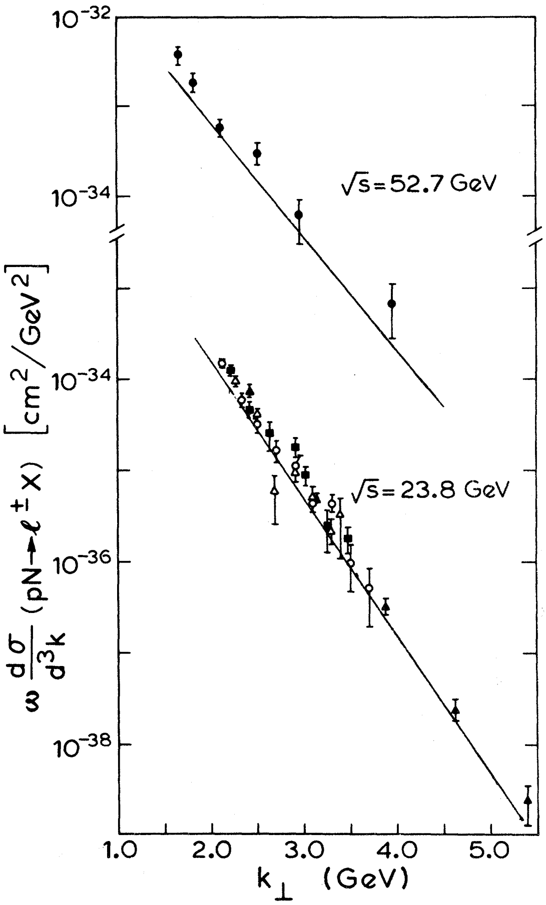

FIG. 1. Comparison of the transverse-momentum and energy dependence of the inclusive lepton distribution at 90°, as calculated by GVDM, to the following experimental data: At $\sqrt{s} = 52.7$ GeV from Ref. 18; at $\sqrt{s} = 23.8$ GeV, ○=μ^+, △=μ^+, ■=$e^\pm$ data from Ref. 19 and ▲=$\mu^\pm$ data from Ref. 20.

discovered $\psi(3.1)$ because of its large branching ratio. The lepton production by ψ has been recently studied in Refs. 15–17; it can be concluded that the contribution from ψ, although significant, accounts for only a fraction of the observed leptons. In particular Ref. 16 concludes that to account for all the observed leptons one needs a ψ production cross section that exceeds recent ISR data[18] by a factor of 3.

Therefore, we have taken $\frac{1}{3}$ of the ψ contribution of Ref. 16 in addition to the contributions from the V_n's of the ρ and ω series. The resulting lepton inclusive cross sections are given in Table I, as well as in Fig. 1, where experimental data[18-20] at $\sqrt{s} = 23.8$ and 52.7 GeV are also presented.

From Fig. 1 it is clear that the combined contributions from the series of vector mesons with the quantum numbers of ρ and ω and from ψ, although probably within experimental errors, fall rather short with respect to the observed number of leptons.

Some additional sources for lepton production, not included in the above calculation, are the following:

(i) *The ϕ meson and its accompanying series of vector mesons (in the spirit of the GVDM).* The branching ratio of $\phi \to l^+l^-$ is known to be relatively large, but, as stated before, the inclusive cross section for $pp \to \phi X$ appears to be too small. It is possible that ϕ and its V_n series produce some extra 10–15% leptons.

(ii) *The newly discovered $\psi'(3.7)$, $\psi''(4.1)$, etc.* The branching ratio of $\psi' \to l^+l^-$ is known to be one order of magnitude lower than that of $\psi(3.1)$; thus one may reasonably expect some extra 5–10% leptons. Preliminary data give $\Gamma(\psi'' \to e^+e^-) \sim 4$ keV (with large error), thus suggesting that the contribution of $\psi''(4.1)$ is of very limited importance.

On the basis of the above calculation we may conclude that the known vector mesons together with their GVDM partners may account for all of the observed leptons at large transverse momenta. A more definitive conclusion should await more experimental information first of all on the large-p_T inclusive cross sections for ρ and ω [see the discussion following Eq. (6)] as well as ψ production: also, from our point of view, some information on $\rho'(1600)$ production as well as ψ', ψ'', etc. production at large p_T would also be very welcomed.

One of us (A. P. C.) would like to thank D. Schiff and M. Fontannaz of Orsay and F. Close and B. Pope of CERN for helpful discussions on direct lepton production at large p_T.

---

[*] Work supported in part by the National Research Council of Canada.

[†] On sabbatical leave from the State University of New York, College of Arts and Sciences, Plattsburgh, New York.

[1] L. Lederman, in *Proceedings of the 1975 International Symposium on Lepton and Photon Interactions at High Energies, Stanford, California*, edited by W. T. Kirk (SLAC, Stanford, 1976); J. W. Cronin, in Lectures at the International School of Subnuclear Physics, Erice, 1975 (unpublished).

[2] J. Appel *et al.*, Phys. Rev. Lett. 35, 9 (1975).

[3] M. Greco, Nucl. Phys. B63, 398 (1973); J. J. Sakurai and D. Schildknecht, Phys. Lett. 40B, 121 (1972); 41B, 489 (1972); 42B, 216 (1972).

[4] D. Schildknecht and F. Steiner, Phys. Lett. 56B, 36 (1975); G. J. Gounaris, Nucl. Phys. B88, 451 (1975).

[5] E. N. Argyres and C. S. Lam, Phys. Rev. Lett. 35, 894 (1975).

[6] S. Brodsky and G. Farrar, Phys. Rev. Lett. 31, 1153 (1973).

[7] D. Sivers, S. Brodsky, and R. Blankenbecler, Phys. Rep. 23C, 1 (1976).

[8] B. Richter, in *Proceedings of the XVII International Conference on High Energy Physics, London, 1974*, edited by J. R. Smith (Rutherford Laboratory, Chilton, Didcot, Berkshire, England, 1974), p. IV-37.

[9] B. Knapp *et al.*, Phys. Rev. Lett. 34, 1044 (1975).

[10] H. A. Gordon, M. Habibi, Kwan-Wu Lai, and I. Stumer, Phys. Rev. Lett. 34, 284 (1975).

[11] M. Deutschmann *et al.*, CERN Report No. CERN/D.Ph. II/PHYS 75-29, 1975 (unpublished).

[12] V. Blobel *et al.*, Phys. Lett. 48B, 73 (1974).

[13] R. N. Cahn, Phys. Rev. D 7, 247 (1973).

[14] Particle Data Group, Phys. Lett. 50B, 1 (1974).

[15] F. Halzen and K. Kajantie, Phys. Lett. 57B, 361 (1975).

[16] G. R. Farrar and R. D. Field, Phys. Lett. 58B, 180 (1975).

[17] F. M. Renard, Nuovo Cimento 29A, 64 (1975).

[18] F. W. Büsser *et al.*, Phys. Lett. 53B, 212 (1974).

[19] J. A. Appel *et al.*, Phys. Rev. Lett. 33, 722 (1974).

[20] J. P. Boymond *et al.*, Phys. Rev. Lett. 33, 112 (1974).