Kinematically accessible vector meson resonance enhancements in $p(K^-, e^+e^-)\Lambda, \Sigma^0, \Lambda(1405)$

Robert A. Williams, Chueng-Ryong Ji, and Stephen R. Cotanch
North Carolina State University, Raleigh, North Carolina 27695
(Received 26 August 1992)

Calculations for the kaon capture, electron pair, and hyperon (Y) production reactions, $p(K^-, e^+e^-)Y$, are made for $Y = \Lambda$, Σ^0, and $\Lambda(1405)$ using our previously developed crossing and duality constrained electroproduction model. Because there is no constraint on the minimum 4-momentum transferred by the timelike photon ($q^2 \geq 2M_e^2 \sim 0$), we observe that the low-lying ρ, ω and ϕ vector mesons are kinematically accessible, producing up to four orders of magnitude enhancement in the theoretical hyperon production cross section. We also discuss the significance and utility of this dramatic enhancement for investigating several important topics of current interest.

PACS number(s): 13.75.Jz, 12.40.Vv, 25.80.Nv

Recently, we have described a hadronic resonance model for kaon electromagnetic production reactions in which duality and crossing symmetry have been exploited to constrain the model parameters [1]. We were able to develop a simultaneous description of the available low and intermediate energy data in both kaon production and capture reaction channels for the interrelated $Y \equiv \Lambda$, Σ^0, and $\Lambda(1405)$ hyperon processes. In this paper, we detail theoretical predictions for the $p(K^-, e^+e^-)Y$ electron pair producing kaon capture reactions. Our main observation is that the low-lying ρ, ω, and ϕ vector mesons are kinematically accessible, since the three-body final state permits the photon to carry a full range of timelike 4-momentum transfer ($q^2 \geq 2M_e^2 \sim 0$). In general, this feature is present for all electron pair producing meson capture reactions of the type $B(M, e^+e^-)B'$ (where M and B represent the incident meson and target baryon, respectively). In contrast, two body processes such as the annihilation reactions, $e^+e^- \leftrightarrow K^+K^-(p\bar{p})$, are constrained to transfer at least $q^2 \geq 4M_K^2$ ($4M_p^2$) by energy conservation, which makes the very important low-q^2 timelike region inaccessible. Since the vector mesons couple strongly to other hadrons, and because they are above threshold in $B(M, e^+e^-)B'$ reactions, there is a dramatic resonant enhancement in the cross section when the photon's 4-momentum transfer approaches the mass of a vector meson (i.e., when $q^2 \to M_v^2$). For $p(K^-, e^+e^-)Y$, we calculate an ehancement of up to four orders of magnitude in the vector meson resonance region (relative to the cross section at $q^2 = 0$). In addition to reporting this novel result, we also discuss the utility and significant ramifications of this clear signature for investigating several important, but potentially small effects, which may be difficult to observe with other reactions.

Before presenting our numerical results, we establish some notation and briefly descibe the model formalism. Because our model is designed to be generally applicable to the crossing related (γ_v, K^+) and (K^-, γ_v) reactions, we must employ an explicitly covariant formulation. A covariant representation of the transition amplitude (t_{fi}) for pseudoscalar meson electroproduction/capture (within the one-photon exchange approximation) can be expressed as the contraction of leptonic ($\mathcal{L}$) and hadronic ($\mathcal{H}$) currents mediated by the photon propagator

$$t_{fi}(h, \lambda', \lambda) = \frac{\mathcal{L}(h) \cdot \mathcal{H}(\lambda', \lambda)}{q^2} \tag{1}$$

where h, λ', λ denote the virtual photon helicity $(0, \pm 1)$, hyperon and proton spins, respectively. Notice that virtual photons are effectively massive, introducing an additional polarization component (longitudinal) corresponding to a helicity zero state. The leptonic current is given by the normal quantum electrodynamics vertex (with $\mathbf{h} \equiv \mathbf{s}_1 + \mathbf{s}_2$)

$$\mathcal{L}^\mu(h) = e \;\; \bar{u}_{e^-}(e_2, s_2)\, \gamma^\mu \, v_{e^+}(e_1, s_1) \;\; , \tag{2}$$

whereas the hadronic current is expressed in terms of six explicitly Lorentz and gauge invariant matrices ($\mathcal{N}_\mu^i$) multiplying scalar functions of the Mandelstam variables, $B_i(q^2, s, t, u)$, the so called invariant (or elementary) amplitudes

$$\mathcal{H}_\mu(\lambda', \lambda) = \bar{u}_Y(l, \lambda') \left(\sum_{i=1}^{6} B_i \, \mathcal{N}_\mu^i \right) u_p(p, \lambda) \;\; . \tag{3}$$

The bilinear covariant matrices ($\mathcal{N}_\mu^i$) are purely kinematical (model independent), whereas the six invariant amplitudes contain all of the reaction dynamics. Our model is based on an effective field hadronic Lagrangian evaluated at the tree level. The elementary amplitudes are obtained by applying the covariant Feynman rules to a specified set of Born and hadronic resonance diagrams. For a detailed account of the resonances included and the resulting expressions for the invariant amplitudes, we refer the reader to our recent paper [1].

Realistic electromagnetic form factors are employed to account for the internal structure of the hadrons in the model. Introducing form factors produces a well-known violation of gauge invariance in the Born graphs due to

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differences between the kaon and proton charges probed by the off-shell photon. We use the standard technique of restoring gauge invariance by modifying the hadronic current density with counter terms proportional to the photon 4-momentum. Specifically,

$$\mathcal{H}_\mu^{\rm nc} \longrightarrow \mathcal{H}_\mu^{\rm c} = \mathcal{H}_\mu^{\rm nc} - \left(\frac{q \cdot \mathcal{H}^{\rm nc}}{q^2}\right) q_\mu, \qquad (4)$$

a conserved current, $\mathcal{H}_\mu^{\rm c}$, is constructed by explicitly subtracting the nonconserved current, $\mathcal{H}_\mu^{\rm nc}$, contracted with the photon's 4-momentum. This procedure exactly restores gauge invariance, however it does not produce any effect on the numerical calculations since all observables are computed from the amplitude, t_{fi} [see Eq. (1)], and $q \cdot \mathcal{L} = 0$ by the Dirac equation.

Vector mesons couple to the interacting hadrons and the e^+e^- pair through the electromagnetic current. The form factor for each hadron has been derived using extended vector meson dominance (EVMD). The general EVMD prescription incorporates several vector mesons (including excited states), an intrinsic form factor for the purely hadronic vertices, and a direct photon-hadron coupling term to allow for a smooth transition to the well-known perturbative QCD scaling behavior (see Ref. [1] for full details). The resulting form factors provide an excellent phenomenological description of the available data for the nucleon and kaon. The G_E^p, G_M^p, and F_{K^+} EVMD parameters have been determined in previous independent investigations [2,3], whereas the $F_{K^*K^+}$ and $F_{K_1K^+}$ transition form factors are predictions of our model resulting from a fit to the kaon electroproduction data [1].

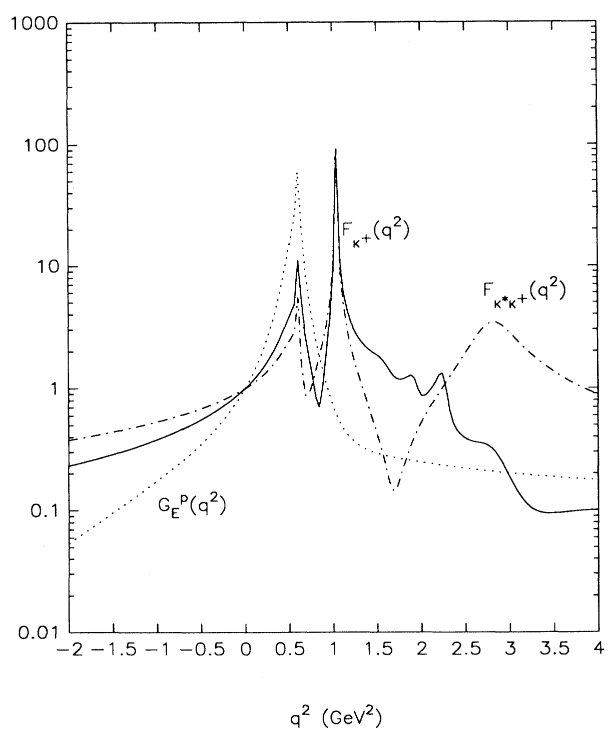

FIG. 1. Spacelike and timelike form factors utilized in our calculations.

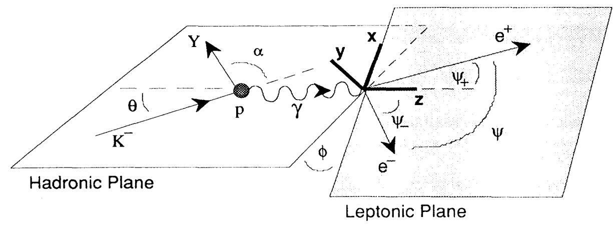

FIG. 2. Convenient frame for the pair producing kaon capture reactions.

We display the functional behavior of these form factors for both spacelike and timelike regions in Fig. 1 (G_M^p is not displayed for clarity). We note that our electroproduction model (for Λ production) involves nine diagrams, each having a corresponding, generally independent, form factor (except the proton graph, which has two). As in our phenomenologically successful electroproduction analysis [1], we take the remaining, poorly known, baryon magnetic and transition form factors to be proportional to G_M^p (with normalization fixed by either $SU(3)_f$ relations, radiative decay widths, or photoproduction data). These assumptions are very reasonable in light of vector meson universality [4] and the approximate SU(3) flavor symmetry of the octet baryons. However, we note that the qualitative features of our prediction for the capture cross sections are independent of these assumptions.

In Fig. 2, we specify a convenient laboratory frame for evaluating the transition amplitude and calculating the differential cross section. Our model predictions are given in Fig. 3, which demonstrate the dramatic effect vector mesons have on the hyperon virtual photoproduction cross section (defined in Ref. [1]) as a function of q^2. The pronounced peaks directly correspond to the resonant timelike vector mesons (ρ, ω, and ϕ) governing the electromagnetic form factors of our model when $q^2 \to M_v^2$. Notice that the vector mesons increase the e^+e^- pair, hyperon production rate by 2–4 orders of magnitude relative to the real photon production rate (cross section at $q^2 = 0$). We note that unitarity corrections may suppress this enhancement somewhat; however, if VMD is fully consistent, then the timelike cross-section magnification should be a persistent, dramatic effect. The differences between the Λ, Σ^0, and Λ(1405) curves simply reflect the sensitivity to their different couplings with the various hadrons included in the model. While the cross section is single peaked as a function of q^2 for a particular vector meson, when expressed in terms of the laboratory system kinematic variables (i.e., the kaon beam momentum, $|\mathbf{k}|$, the angle between the leptonic and hadronic scattering planes, ϕ, the final state hyperon angle α, the virtual photon angle θ, and the electron or positron angle $\psi_\pm$) it can be dual peaked as indicated in Figs. 4 and 5. In general, the condition $q^2 \to M_v^2$ permits multivalued solutions in terms of laboratory frame variables. This useful feature will enable an experimentalist to choose the most convenient arrangement of detectors for observing a particular vector meson resonance.

While the experimental confirmation of our predictions for $p(K^-, e^+e^-)Y$ may be of intrinsic interest, we

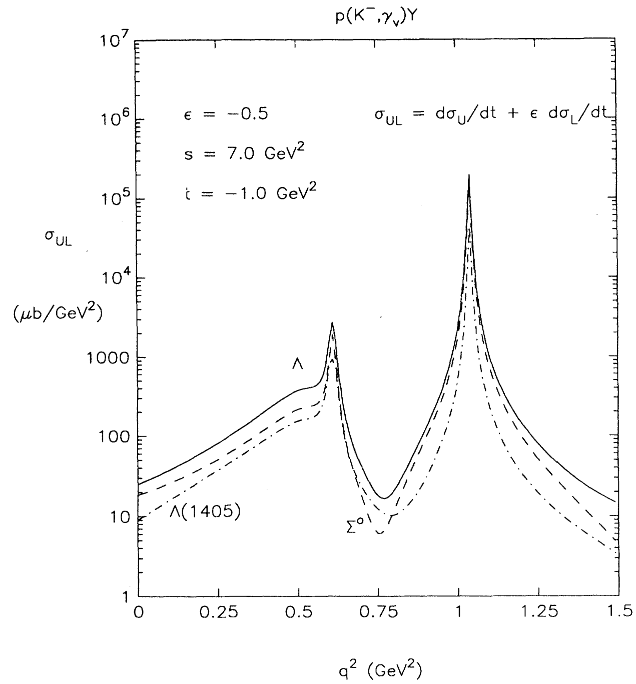

FIG. 3. Two-body virtual photon radiative capture cross section as a function of q^2.

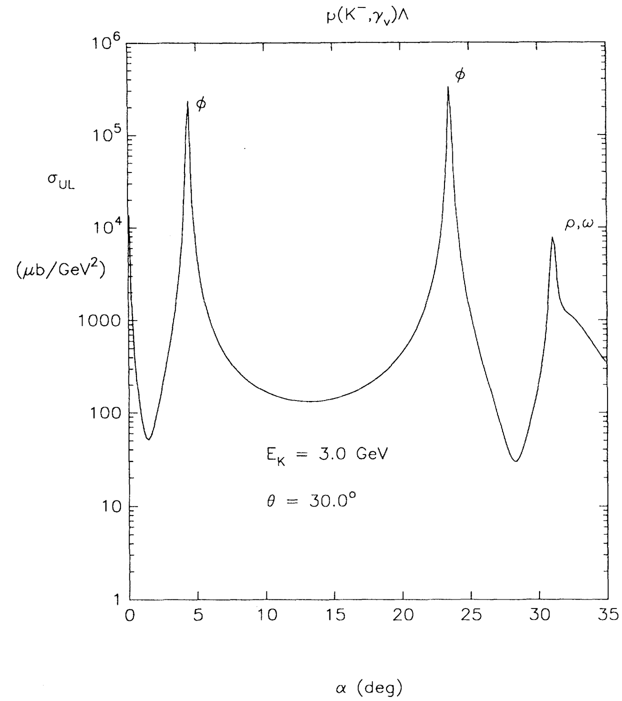

FIG. 5. A doubling of detector positions, which will observe a specific vector meson resonance, is seen in the two-body unpolarized virtual photon radiative capture cross section as a function of the hyperon angle. The kinematics were chosen to maximize q^2 through the constraint $\psi_+ = \psi_-$.

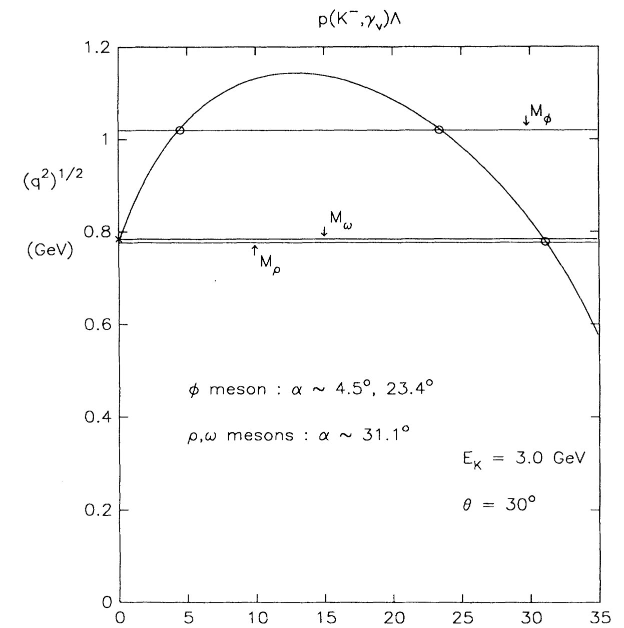

FIG. 4. Location of vector meson resonances as a function of the Λ hyperon angle α for 3 GeV incident kaons and photons emitted at 30° in the lab frame. The resonant α positions occur when $\sqrt{q^2} \to M_\nu$ (i.e., points of intersection between the curve and horizontal lines).

note that several exciting possibilities exist for using $B(M,e^+e^-)B'$ meson capture to obtain new information about novel, potentially small effects that may be difficult to observe with other reactions. In particular, meson capture can be utilized for investigating the following diverse topics: (1) strangeness content of the nucleon, (2) medium modifications of static hadron properties, (3) magnification of small amplitude processes (such as the parity violating weak decay of hyperons), and (4) extracting electromagnetic form factors in the previously unobserved low-q^2 timelike region. The essential feature, which can be exploited is the accessibility of vector mesons with the corresponding resonant enhancement of the cross section. The vector meson resonances provide a clear, unambiguous signature from which important new information can be extracted, as we now detail.

The recent European Muon Collaboration (EMC) measurement of the proton's spin structure function [5] suggests the spin carried by strange sea quarks is roughly equal to the spin carried by the u- and d-valence quarks. This result appears to be in contradiction with the normal quark model assignment of spin to only u- and d-valence quarks in the nucleon. Several theoretical attempts to explain the EMC data without strangeness in the proton have been proposed [6], however, there is presently no consensus, and further study is obviously warranted. Recently, there has been a proposal to measure the strangeness content of the nucleon by leptoproduction of the ϕ meson [7]. Due to the pure $s\bar{s}$ structure of the ϕ, the hadronic coupling of the ϕ to a hadron is directly related to the hadron's strangeness content [8]. For a nucleon with no $s\bar{s}$ component, the hadronic coupling ($g_{\phi NN}$) should be OZI (Okubo, Zweig, and Iizuka) *suppressed* (couple only through gluons). With appreciable strangeness however, the ϕN coupling would be *OZI evading.* We propose a complementary use of the ϕ meson for measuring strangeness in the nucleon through the use of pion capture reactions $N(\pi, l^+l^-)N$. The benefit of pion capture lepton pair production is that the ϕ, which does not couple to the pion, couples to the nucleon (assuming strangeness content) through the electromagnetic current in the timelike momentum transfer region, which in analogy to (K^-, e^+e^-), will produce a large, unambiguous resonance signature in the cross section. The ϕN coupling can be extracted, and thus the nucleon strangeness content inferred, from the magnitude of the resonant cross section.

Meson capture on nuclei can be utilized to investigate the modification of static hadron properties by the nuclear medium. In particular, several theoretical calculations predict a change of mass and decay constants for hadrons in a nuclear environment [9]. The presence of such medium effects would be evident by any distinct change in a vector meson's resonance shape (position, width, and/or height). The magnitude of the resonant cross section will also provide evidence for any renormalization of the hadronic coupling in the nuclear medium. For spacelike reactions, such as electroproduction, there is no resonance signature; hence the medium effect is less obvious and direct experimental observation becomes increasingly difficult.

The high count rates expected for $p(K^-, e^+e^-)Y$ make this type of reaction particularly useful as a tool for quantitative investigations of the weak and radiative decay of hyperons. Decay rates and branching fractions of the hyperons can be measured with a higher degree of precision due to the enhanced flux of hyperons produced by kaon capture in the vector meson resonance region. Hyperon decay measurements are important for studying parity violating asymmetries such as the magnitude and relative phases of parity-violating versus parity-conserving amplitudes (for example, see Ref. [13]), and also for testing various quark, soliton, and hadron model predictions such as in Refs. [10], [11], and [12], respectively. The $\Lambda(1405)$ is particularly interesting due to its controversial quark structure [14]. Measuring the decay properties of the $\Lambda(1405)$ hyperon resonance will help discriminate between different proposed exotic structures (i.e., an octet mixed qqq state or molecular $q\bar{q}$-qqq system).

Finally, we discuss the importance of pair producing meson capture for extracting electromagnetic form factors. Interest in electromagnetic form factors is prevalent, as demonstrated by the number and frequency of recently published quark model calculations, and committed experimental effort devoted to this subject. With (M, e^+e^-) reactions, an exciting possibility exists for extracting electromagnetic form factors in the previously unobserved low-q^2 timelike region. Essentially all of the timelike measurements performed to date utilize annihilation reactions, which kinematically exclude the low-lying vector meson resonance region due to a large threshold energy (except for pion reactions). In a subsequent communication, we detail how our model can be used to analyze future $K^-(p, e^+e^-)Y$ data to simultaneously extract up to six independent electromagnetic form factors in this important, unobserved region. Because each of the six invariant amplitudes (B_i) involves a linear combination of N photoproduction amplitudes (b_i^k) multiplying the electromagnetic form factors ($\mathcal{F}_k$)

$$B_i(s,t,q^2) = \sum_{k=1}^{N} b_i^k(s,t)\ \mathcal{F}_k(q^2) \ , \tag{5}$$

it is possible to invert this relation (under certain theoretical model constraints) to obtain the form factors in terms of the experimentally determined invariant amplitudes. The major difficulty of this form factor inversion procedure is the challenging experimental effort required to determine the six elementary amplitudes. This is accomplished by measuring a *"complete set"* of polarization asymmetry observables. There are a total of eleven independent measurements that are needed to completely specify the magnitude and relative phases of the six complex scalar amplitudes. We defer a detailed discussion to our subsequent paper but stress here that electromagnetic form factors can be extracted from experimental data by using a reliable phenomenological model in conjunction with the amplitude inversion procedure.

In conclusion, the electron pair producing meson capture reactions of the type $B(M, e^+e^-)B'$ are significant because the low-lying ρ, ω, and ϕ vector mesons are kinematically accessible. We made an explicit calculation of the $p(K^-, e^+e^-)Y$ reactions for $Y = \Lambda$, Σ^o and $\Lambda(1405)$ and found a dramatic resonant enhancement of up to four orders of magnitude in the hyperon production cross section relative to real photon radiative capture. The accessible vector meson resonances in (M, e^+e^-) are novel phenomena, which provide a distinct experimental signature for investigating potentially small theoretical effects. We have explicitly discussed the benefits of using (M, e^+e^-) processes to probe the nucleon's strangeness content, medium modifications of hadronic properties, weak and radiative hyperon decays, and for extracting timelike electromagnetic form factors in a new kinematic regime.

We gratefully acknowledge financial support from U.S. Department of Energy Grants DE-FG05-88ER40461 and DE-FG05-90ER40589. We also thank the North Carolina Supercomputing Center for the grant of Cray Y-MP time.

[1] Robert A. Williams, Chueng-Ryong Ji, and Stephen R. Cotanch, Phys. Rev. C **46**, 1617 (1992).
[2] M. F. Gari and W. Krumpelmann, Z. Phys. A **322**, 689 (1985); Phys. Lett. B **173**, 10 (1986); Phys. Rev. D **45**, 1817 (1992).
[3] F. Felicetti and Y. Srivastava, Phys. Lett. **107B**, 227 (1981).
[4] J. J. Sakurai, Ann. Phys. (N.Y.) **11**, 1 (1960).

[5] EM Collaboration, J. Ashman *et al.*, Phys. Lett. B **206**, 364 (1988); Nucl. Phys. **B328**, 1 (1989).

[6] M. A. Nowak, J. J. M. Verbaarshot, and I. Zashed, Phys. Lett. B **217**, 157 (1989); H. Fritzch, *ibid.* **229**, 122 (1989); Mod. Phys. Lett. A **5**, 1815 (1990); R. Anselmino and M. D. Scadron, Phys. Lett. B **229**, 117 (1989); J. Stern and G. Clement, Phys. Lett. B **231**, 471 (1989); V. Bernard and U. Meissner, *ibid.* **216**, 392 (1989); **223**, 439 (1989); R. L. Jaffe and A. Manohar, Nucl. Phys. **B337**, 509 (1990); J. Gasser, H. Leutwyler, and M. E. Sainio, Phys. Lett. B **253**, 252 (1991).

[7] E. M. Henley, G. Krein, and A. G. Williams, Phys. Lett. B **281**, 178 (1992).

[8] J. Ellis, E. Gabathuler, and M. Karliner, Phys. Lett. B **217**, 173 (1989).

[9] G. E. Brown and Mannque Rho, Phys. Rev. Lett. **66**, 2720 (1991); Kuniharu Kubodera and Mannque Rho, *ibid.* **67**, 3479 (1991); C. J. Horowitz and Brian D. Serot, Nucl. Phys. **A464**, 613 (1987).

[10] Simon Capstick and Nathan Isgur, Phys. Rev. D **34**, 2809 (1986).

[11] C. Gobbi, D. O. Riska, and N. N. Scoccola, Nucl. Phys. **A999**, 671 (1992).

[12] F. M. Renard and Y. Renard, Nuovo Cimento **55A**, 631 (1968).

[13] A. J. Noble *et al.,* Phys. Rev. Lett. **69**, 414 (1992).

[14] R. H. Dalitz and S. F. Tuan, Phys. Rev. Lett. **2**, 425 (1959); R. C. Arnold and J. J. Sakurai, Phys. Rev. **128**, 2808 (1962); D. Gromes, Z. Phys. C **18** 249 (1983); E. A. Veit *et al.*, Phys. Rev. D **31**, 1033 (1985); **31**, 2242 (1985).