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Proton and Charged Kaon Timelike Form Factors at $\sqrt{s} = 3.67$ GeV*

S. Dobbs,[1] Z. Metreveli,[1] K. K. Seth,[1] A. Tomaradze,[1] P. Zweber,[1] J. Ernst,[2] K. Arms,[3] H. Severini,[4] D. M. Asner,[5] S. A. Dytman,[5] W. Love,[5] S. Mehrabyan,[5] J. A. Mueller,[5] V. Savinov,[5] Z. Li,[6] A. Lopez,[6] H. Mendez,[6] J. Ramirez,[6] G. S. Huang,[7] D. H. Miller,[7] V. Pavlunin,[7] B. Sanghi,[7] I. P. J. Shipsey,[7] G. S. Adams,[8] M. Cravey,[8] J. P. Cummings,[8] I. Danko,[8] J. Napolitano,[8] Q. He,[9] H. Muramatsu,[9] C. S. Park,[9] E. H. Thorndike,[9] T. E. Coan,[10] Y. S. Gao,[10] F. Liu,[10] R. Stroynowski,[10] M. Artuso,[11] C. Boulahouache,[11] S. Blusk,[11] J. Butt,[11] O. Dorjkhaidav,[11] J. Li,[11] N. Menaa,[11] R. Mountain,[11] R. Nandakumar,[11] K. Randrianarivony,[11] R. Redjimi,[11] R. Sia,[11] T. Skwarnicki,[11] S. Stone,[11] J. C. Wang,[11] K. Zhang,[11] S. E. Csorna,[12] G. Bonvicini,[13] D. Cinabro,[13] M. Dubrovin,[13] A. Bornheim,[14] S. P. Pappas,[14] A. J. Weinstein,[14] R. A. Briere,[15] G. P. Chen,[15] J. Chen,[15] T. Ferguson,[15] G. Tatishvili,[15] H. Vogel,[15] M. E. Watkins,[15] J. L. Rosner,[16] N. E. Adam,[17] J. P. Alexander,[17] K. Berkelman,[17] D. G. Cassel,[17] V. Crede,[17] J. E. Duboscq,[17] K. M. Ecklund,[17] R. Ehrlich,[17] L. Fields,[17] R. S. Galik,[17] L. Gibbons,[17] B. Gittelman,[17] R. Gray,[17] S. W. Gray,[17] D. L. Hartill,[17] B. K. Heltsley,[17] D. Hertz,[17] C. D. Jones,[17] J. Kandaswamy,[17] D. L. Kreinick,[17] V. E. Kuznetsov,[17] H. Mahlke-Krüger,[17] T. O. Meyer,[17] P. U. E. Onyisi,[17] J. R. Patterson,[17] D. Peterson,[17] E. A. Phillips,[17] J. Pivarski,[17] D. Riley,[17] A. Ryd,[17] A. J. Sadoff,[17] H. Schwarthoff,[17] X. Shi,[17] M. R. Shepherd,[17] S. Stroiney,[17] W. M. Sun,[17] D. Urner,[17] T. Wilksen,[17] K. M. Weaver,[17] M. Weinberger,[17] S. B. Athar,[18] P. Avery,[18] L. Breva-Newell,[18] R. Patel,[18] V. Potlia,[18] H. Stoeck,[18] J. Yelton,[18] P. Rubin,[19] C. Cawlfield,[20] B. I. Eisenstein,[20] G. D. Gollin,[20] I. Karliner,[20] D. Kim,[20] N. Lowrey,[20] P. Naik,[20] C. Sedlack,[20] M. Selen,[20] E. J. White,[20] J. Williams,[20] J. Wiss,[20] K. W. Edwards,[21] D. Besson,[22] T. K. Pedlar,[23] D. Cronin-Hennessy,[24] K. Y. Gao,[24] D. T. Gong,[24] J. Hietala,[24] Y. Kubota,[24] T. Klein,[24] B. W. Lang,[24] S. Z. Li,[24] R. Poling,[24] A. W. Scott,[24] and A. Smith[24]

(CLEO Collaboration)

[1]*Northwestern University, Evanston, Illinois 60208*
[2]*State University of New York at Albany, Albany, New York 12222*
[3]*Ohio State University, Columbus, Ohio 43210*
[4]*University of Oklahoma, Norman, Oklahoma 73019*
[5]*University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[6]*University of Puerto Rico, Mayaguez, Puerto Rico 00681*
[7]*Purdue University, West Lafayette, Indiana 47907*
[8]*Rensselaer Polytechnic Institute, Troy, New York 12180*
[9]*University of Rochester, Rochester, New York 14627*
[10]*Southern Methodist University, Dallas, Texas 75275*
[11]*Syracuse University, Syracuse, New York 13244*
[12]*Vanderbilt University, Nashville, Tennessee 37235*
[13]*Wayne State University, Detroit, Michigan 48202*
[14]*California Institute of Technology, Pasadena, California 91125*
[15]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213*
[16]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637*

[17]*Cornell University, Ithaca, New York 14853*
[18]*University of Florida, Gainesville, Florida 32611*
[19]*George Mason University, Fairfax, Virginia 22030*
[20]*University of Illinois, Urbana-Champaign, Illinois 61801*
[21]*Carleton University, Ottawa, Ontario, Canada K1S 5B6*
and the Institute of Particle Physics, Canada
[22]*University of Kansas, Lawrence, Kansas 66045*
[23]*Luther College, Decorah, Iowa 52101*
[24]*University of Minnesota, Minneapolis, Minnesota 55455*

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Abstract

We report on the measurement of the electromagnetic form factors of the proton and charged kaon for timelike momentum transfer of $|Q^2| = 13.48$ GeV^2 using 20.7 pb^{-1} of e^+e^- data taken at $\sqrt{s} = 3.671$ GeV with the CLEO-c detector. The preliminary result for the magnetic form factor of the proton, assuming $|G_E^P(s)| = |G_M^P(s)|$, is $|G_M^P(13.48 \text{ GeV}^2)| = 0.0139^{+0.0024}_{-0.0018}(stat)^{+0.0006}_{-0.0003}(syst)$, which agrees with the earlier Fermilab measurements. The charged kaon electromagnetic form factor, $|F_K(13.48 \text{ GeV}^2)| = 0.0628 \pm 0.0038(stat) \pm 0.0014(syst)$, is the first precision measurement for $|Q^2| > 4$ GeV^2.

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Electromagnetic form factors of composite particles provide deep insight into their structure and play an important role in determining the validity of perturbative QCD. Precision measurements of the proton form factor for spacelike momentum transfers have been made up to $Q^2 = 30$ GeV^2 by the study of ep elastic scattering [1], where Q^2 is the four-momentum squared carried by the virtual photon, with $Q^2 > 0$ ($Q^2 < 0$) for spacelike (timelike) momentum transfers. Recently, the form factor of the proton for timelike momentum transfers in the region $|Q^2| = 9$-14 GeV^2 have been reported by the study of the reaction $p\overline{p} \to e^+e^-$ [2], and it is found that, while its variation with $|Q^2|$ appears to conform to the expectations of perturbative QCD, its magnitude is, rather surprisingly, nearly twice as large as that of the corresponding spacelike form factor. The interpretation of the form factors of pseudoscalar mesons, pions and kaons, is in principle simpler, but poses more difficult experimental problems. Spacelike form factors cannot be directly measured because meson targets are not possible, and timelike form factors at large $|Q^2|$ can only be measured at e^+e^- colliders of sufficient energy and with detectors capable of excellent particle identification. As a result, no good measurements of either spacelike or timelike form factors of either the pion or kaon form factors exist in the literature.

In this paper, we report results for the timelike form factor of the proton and charged kaon for $|Q^2| = 13.48$ GeV^2 by precision measurements of the reactions $e^+e^- \to p\overline{p}$ and $e^+e^- \to K^+K^-$. For the proton, we confirm the Fermilab results with comparable precision, and, for the charged kaon, we present the first precision measurement for $|Q^2|$ larger than 4 GeV^2.

The data were collected at the Cornell Electron Storage Ring (CESR) with the detector in the CLEO-c configuration [3]. The detector is cylindrically symmetric and provides 93% coverage of solid angle for charged and neutral particle identification. The detector components important for this analysis are the 6-layer wire vertex detector (ZD), main 47-layer drift chamber (DR), ring-imaging Cherenkov detector (RICH), and CsI crystal calorimeter (CC). They are operated within a 1.0 T magnetic field produced by a superconducting solenoid located directly outside of the CC. The ZD and DR detect charged particles and the DR provides measurement of their momenta with a precision of ∼0.6% at $p = 1$ GeV/c and ionization energy loss (dE/dx). The combination of dE/dx and information from the RICH detector allows for separating different charged particle species. The CC allows precision measurements of electromagnetic shower energy and position.

The data sample consists of e^+e^- collisions at $\sqrt{s} = 3.671$ GeV with a total integrated luminosity of 20.7 pb^{-1} with center-of-mass rms energy spread of 2.3 MeV.

The proton and kaon timelike form factors are related to the differential cross section for their pair production at $\sqrt{s}$ as follows

$$\frac{d\sigma_0}{d\Omega}(e^+e^- \to p\overline{p}) = \frac{\alpha^2}{4s}\beta_p[|G_M^P(s)|^2\ (1+\cos^2\theta) + \frac{4m_p^2}{s}|G_E^P(s)|^2(\sin^2\theta)], \tag{1}$$

$$\frac{d\sigma_0}{d\Omega}(e^+e^- \to K^+K^-) = \frac{\alpha^2}{8s}\ \beta_K^3\ |F_K(s)|^2\sin^2\theta, \tag{2}$$

where α is the fine-structure constant, β_p and β_K are the proton and kaon velocity, respectively, in the laboratory system, $|G_M^P(s)|$ and $|G_E^P(s)|$ are the magnetic and electric form factors of the proton, $|F_K(s)|$ is the electric form factor of the spin 0 kaon, and θ is the laboratory angle between the proton (kaon) and the positron beam.

A fully reconstructed event has two charged particles and zero net charge. Each charged particle must have $|\cos\theta| < 0.8$ in order to transverse the RICH detector and is required to satisfy standard requirements for track quality and distance of closest approach to the interaction point. For the $p\overline{p}$ final state, the two charged particles must have a net momentum < 100 MeV/c, and, for the K^+K^- final state, they must have a net momentum < 60 MeV/c. Signal-to-background studies are performed to optimize the combined dE/dx-RICH particle identification criteria for l^+l^- background suppression, where $l = e, \mu$. The optimization studies also suggest to select $p\overline{p}$ events when the positively charged particle has a CC energy to DR momentum ratio (E/p) of $E/p < 0.85$ and K^+K^- events when both charged particles have $E/p < 0.85$. The signal yields are extracted from a center-of-mass energy normalized variable defined as the sum of the energy of the two tracks assuming the particle species of interest for each track. Figure 1 shows the events which satisfy the $p\overline{p}$ and K^+K^- final state event selection criteria.

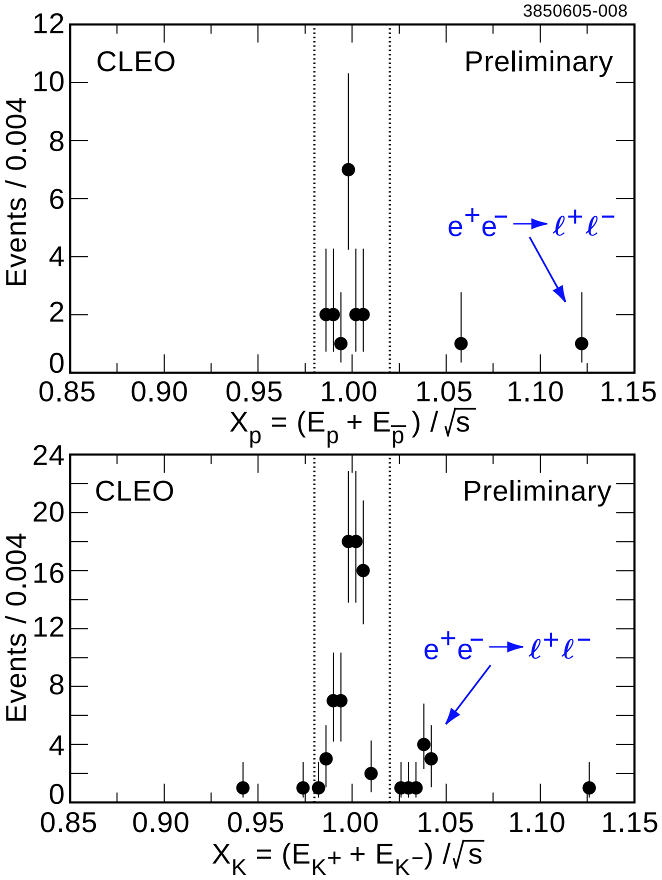

FIG. 1: Data events as a function of $X_h \equiv (E_{h+} + E_{h-})/\sqrt{s}$ for $p\overline{p}$ (top) and K^+K^- (bottom) final states. The dashed lines denote the signal regions defined as $0.98 < X_h < 1.02$. The mean value of the leptonic $\mu + e$ background is also shown.

The Born cross section for hadron pair ($p\overline{p}$ or K^+K^-) production is determined by

$$\sigma_0(e^+e^- \rightarrow h^+h^-) = \frac{N}{\epsilon\mathcal{L}(1+\delta)}, \tag{3}$$

where N is the number of signal events after correcting for $\psi(2S)$ and leptonic background contamination, ϵ is the detection efficiency, $\mathcal{L}$ is the total integrated luminosity, and $1 + \delta$

is the radiative correction associated with h^+h^- production from e^+e^- annihilations. The detection efficiencies are determined by studying $e^+e^- \rightarrow h^+h^-$ signal Monte Carlo (MC) samples, where h = K, p, using GEANT 3.21/11 [4] to simulate the CLEO-c detector. The $e^+e^- \rightarrow K^+K^-$ MC sample is generated with a $\sin^2\theta$ angular distribution. The $e^+e^- \rightarrow p\overline{p}$ MC sample is generated with two different assumptions, $|G_E^P(s)| = 0$ with $\sigma(\theta) \propto 1 + \cos^2\theta$ and $|G_E^P(s)| = |G_M^P(s)|$ with $\sigma(\theta) \propto 1 + (0.59)\cos^2\theta$. The initial state radiative corrections are determined using the method of Bonneau and Martin [5] with the addition of μ and τ pair loops to the vacuum polarization term. For $e^+e^- \rightarrow p\overline{p}$, we obtain $1 + \delta = 0.853$ for $|G_E^P(s)| = 0$ and $1 + \delta = 0.860$ for $|G_E^P(s)| = |G_M^P(s)|$. For $e^+e^- \rightarrow K^+K^-$, we obtain $1 + \delta$ $= 0.810$.

The angle-integrated yields are $N(e^+e^- \rightarrow p\overline{p}) = 14.08^{+4.80}_{-3.67}$ and $N(e^+e^- \rightarrow K^+K^-) = 70.9 \pm 8.5$. These lead to the results listed in Table I. Systematic uncertainties which arise from possible biases in the event selection criteria, and treatment of the $\psi(2S)$ contamination, leptonic background, and radiative correction have been studied and are incorporated in the results presented in the table.

TABLE I: Results for integrated cross sections and electromagnetic form factors. N is the number of signal events after correcting for $\psi(2S)$ and leptonic background contamination, ϵ is the detection efficiency. The first error is statistical and the second is systematic.

Final State	N	ϵ_p	$\sigma_0(e^+e^- \rightarrow p\overline{p})$ (pb)	$\vert G_M^P(13.48 \text{ GeV}^2)\vert$
$p\overline{p}$ ($\vert G_E^P(s)\vert = 0$)	$14.08^{+4.80}_{-3.67}$	0.626	$1.27^{+0.43+0.11}_{-0.33-0.06}$	$0.0152^{+0.0026+0.0007}_{-0.0020-0.0003}$
$p\overline{p}$ ($\vert G_E^P(s)\vert = \vert G_M^P(s)\vert$)	$14.08^{+4.80}_{-3.67}$	0.657	$1.20^{+0.41+0.11}_{-0.31-0.06}$	$0.0139^{+0.0024+0.0006}_{-0.0018-0.0003}$

Final State	N	ϵ_K	$\sigma_0(e^+e^- \rightarrow K^+K^-)$ (pb)	$\vert F_K(13.48 \text{ GeV}^2)\vert$
K^+K^-	70.9±8.5	0.743	5.69±0.68±0.25	0.0628±0.0038±0.0014

Figure 2 shows our result for the timelike magnetic form factor of the proton in terms of $|Q^4||G_M^P(s)|/\mu_p$ together with earlier results under the assumption $|G_E^P(s)| = |G_M^P(s)|$. Our result for $|Q^2| = 13.48$ GeV^2 is in good agreement with the Fermilab (E835) results at $|Q^2| = 12.43$ and 13.11 GeV^2, obtained from the study of the reverse reaction $p\overline{p} \rightarrow e^+e^-$, and confirms the $\alpha^2(strong)$ dependence predicted by pQCD, as well as the empirical observation that the timelike form factors are nearly a factor two larger than the spacelike form factors.

Figure 3 shows a compilation of the existing world data for the timelike form factors of the charged kaon in terms of $|Q^2||F_K(s)|$. No earlier result for experimentally identified kaons exist above $|Q^2| > 4$ GeV^2. Our result for $|Q^2| = 13.48$ GeV^2 is the first precision measurement for $|Q^2| > 4$ GeV and appears to support the $\alpha(strong)$ dependence predicted by pQCD.

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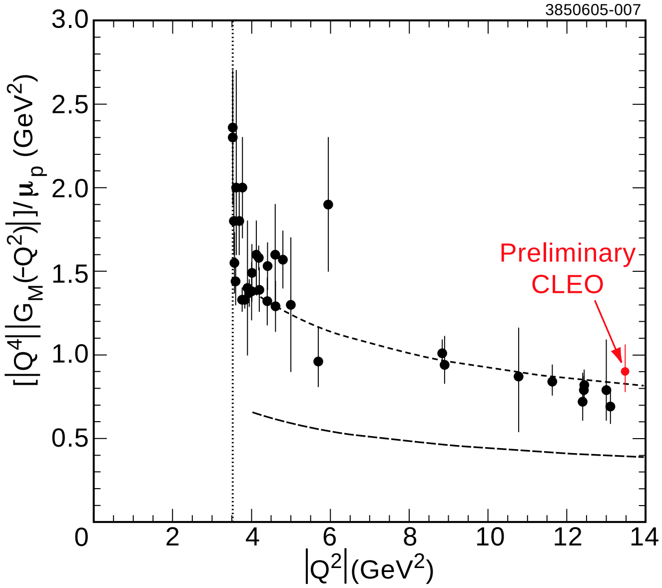

FIG. 2: Compilation of the existing experimental data for the proton magnetic form factor with timelike momentum transfer assuming $|G_E^P(s)| = |G_M^P(s)|$. The solid black points are from Refs. [2, 6]. The vertical dotted line specifies the threshold for $p\overline{p}$ production, i.e., $|Q^2| = (2m_p)^2 = 3.52$ GeV^2. The dashed line is the fit result of $|Q^4||G_M(-Q^2)|/\mu_p \propto \alpha_s^2(|Q^2|)$ for the timelike form factor data for events with $|Q^2| > 4$ GeV^2 and the lower dotted line is the fit result for the spacelike form factor (data not shown). A nearly factor two difference is apparent between the timelike and spacelike form factors.

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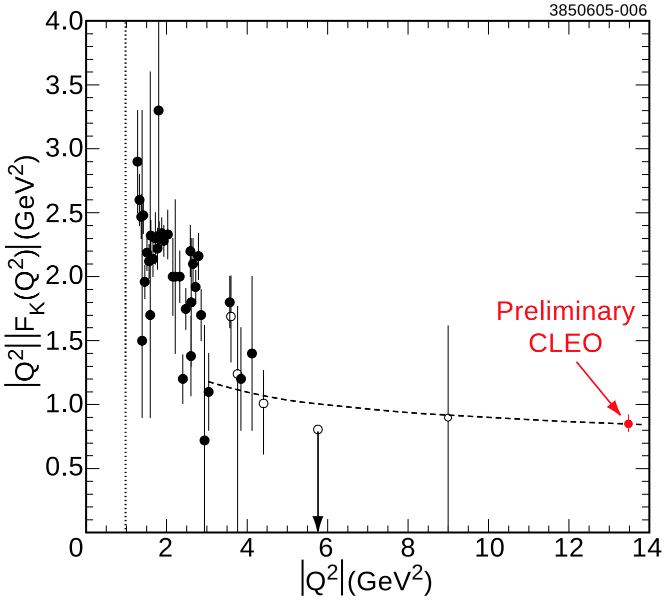

FIG. 3: Compilation of the existing experimental data for the kaon form factor with timelike momentum transfer. The solid black and open points are from Refs. [7]. The solid black points are direct measurements of the K^+K^- final state while the open points are based on measurements where pions and kaons could not be experimentally separated and were divided by making VDM based assumptions. The present result is shown as the last point in the plot. The vertical dotted line specifies the threshold for K^+K^- production, i.e., $|Q^2| = (2m_K)^2 = 0.975$ GeV^2. The dashed line is the fit result of $|Q^2||F_K(-Q^2)| \propto \alpha_s(Q^2)$ for events with $|Q^2| > 3$ GeV^2.

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