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Elastic Electroproduction of ϕ Mesons at Large Q^2 at HERA

H1 Collaboration

Abstract

A measurement of the cross section for the elastic electroproduction of ϕ mesons is presented in the range $6 < Q^2 < 25$ GeV^2 and $40 < W < 130$ GeV/c^2, using data obtained with the H1 detector in 1994, corresponding to an integrated luminosity of 2.5 pb^{-1}. The cross section is measured for two bins in Q^2. The Q^2 and t dependences of the cross section and the polarisation state of the electroproduced ϕ mesons are presented. The ratio of the elastic production cross sections for ϕ and ϱ mesons is found to increase with Q^2 and, for the same values of Q^2, to be higher for the present measurement than for the lower energy fixed target experiments.

1 Introduction

The diffractive production of vector mesons at the ep collider HERA, at high energy, is expected to shed light on the nature and the characteristics of the diffractive exchange.

Contrasting pictures are obtained for different vector mesons and different photon virtualities. On the one hand, ϱ meson production by (quasi) real photons with $Q^2 \simeq 0$ [1, 2] exhibits the behaviour typical of hadronic interactions, in particular a slow increase of the cross section with energy: $\sigma\ (\gamma + p \rightarrow \varrho + p) \propto W^{4\Delta}$, where W is the centre of mass energy of the γp system and $\Delta \approx 0.08$ [3], an exponential fall off of the cross section with $|t|$, $\mathrm{d}\sigma\ /\mathrm{d}t \propto e^{bt}$, t being the four-momentum squared transferred to the proton, and shrinkage of the diffraction peak, i.e. increase of the b slope with increasing energy. The photoproduction of ϱ mesons is thus essentially attributed to soft pomeron exchange, dominated by QCD non-perturbative features. On the other hand, the cross section for photoproduction of J/ψ mesons [4, 5] increases much faster with energy than for the ϱ ($\Delta \approx 0.25$), as qualitatively expected for a hard process where the pomeron is interpreted as a two gluon exchange [6, 7]. This behaviour is generally attributed, in a perturbative QCD approach, to the large mass of the charm quark and the small spatial extension of the J/ψ wave function. As for vector meson electroproduction with $Q^2 \gtrsim 8$ GeV^2, ϱ production [8, 9] reveals features indicative of a transition regime between soft and hard processes (moderate cross section increase with energy, shrinkage of the diffractive peak), whereas the behaviour of the J/ψ cross section is quite similar to that of photoproduction [8].

In these circumstances, it is particularly interesting to study the electroproduction of ϕ mesons, which have a mass intermediate between those of the ϱ and J/ψ mesons, and presumably a more compact wave function than the ϱ meson. In photoproduction, fixed target [10, 11] experiments and the ZEUS Collaboration [12] report features typical of soft diffractive interactions, similar to the ϱ case [1]. At higher Q^2, the ϕ behaviour could be intermediate between those of the ϱ and of the J/ψ. Of particular interest is the evolution of the ϕ/ϱ cross section ratio with Q^2 and W. This ratio is measured in photoproduction to be well below the value 2/9 expected from quark charge counting and SU(3) symmetry. Both in the soft pomeron [13] and in the perturbative QCD approaches [14] the ratio should increase with Q^2, and in the latter case, it is expected to exceed the value 2/9 at high Q^2.

The only existing data on ϕ meson electroproduction for $Q^2 \gtrsim 6$ GeV^2 are from the EMC [15] and NMC [16] Collaborations at $\langle W \rangle \approx 14$ GeV/c^2 and the ZEUS Collaboration [17] at HERA [2]. We report here [20] on the data obtained in 1994 by the H1 Collaboration, when HERA operated with 820 GeV protons and 27.5 GeV positrons. They correspond to an integrated luminosity of 2.5 pb^{-1}.

[1] Note that, following the Zweig rule, reggeon exchange does not contribute to elastic ϕ production, thus leading to a monotonic increase of the cross section at low energy, at variance with ϱ production.

[2] The electroproduction of ϕ mesons at $Q^2 \lesssim 2$ GeV^2 has also been measured in fixed target experiments for $W < 4$ GeV/c^2 [18] and for $W \approx 12$ GeV/c^2 [19].

2 Event selection and kinematics

A detailed description of the H1 detector can be found elsewhere [21]. The process under study is

$$e^+ + p \to e^+ + \phi + p \;\; ; \;\; \phi \to K^+ + K^-, \tag{1}$$

where the intermediate photon is highly virtual (see Fig. 1a).

The events selected in the H1 detector thus contain only a positron and two kaon candidates with opposite charges, originating from a vertex situated in the nominal e^+p interaction region. The scattered proton remains in the beam pipe and is not detected because of the small momentum transfer to the target in diffractive interactions.

The scattered positron is identified as an electromagnetic cluster of energy larger than 15 GeV detected in the H1 backward electromagnetic calorimeter BEMC, associated with a hit in the multiwire proportional chamber BPC sitting in front of the BEMC [3]. To ensure good trigger efficiency and good precision of the kinematic variable measurement, the centre of gravity of the cluster associated with the positron must be reconstructed in the BEMC region outside a square of 32×32 cm^2 around the beam pipe, the energy deposited in this region must be larger than 10 GeV, and the distance between the BPC hit and the cluster centre of gravity projection onto the BPC plane must be less than 4 cm. Two tracks of opposite signs, corresponding to particles with a momentum transverse to the beam direction larger than 100 MeV/c, must be reconstructed in the H1 central tracking detector, and define a vertex lying at a distance less than 35 cm from the nominal interaction point. The charge and momentum of the particles are measured thanks to the uniform 1.15 T magnetic field in the central part of the detector. No particle identification is required.

A background to reaction (1) is due to diffractive events in which the proton is excited in a system of higher mass, which subsequently dissociates (see Fig. 1b). The H1 forward detectors reduce efficiently this background [5, 8, 22]. For the present analysis, a total energy smaller than 1 GeV must be measured in the forward part of the liquid argon calorimeter in the pseudorapidity range $\eta > 2$ [4], no more than 1 hit pair must be detected in the first three layers of the forward muon system, and no hit must be registered in the proton remnant tagger situated 24 m from the ep interaction point.

The event kinematics are reconstructed using the double angle method [23] from the polar angles of the scattered positron (measured from the positions of the BPC hit and of the interaction vertex) and of the ϕ candidate (obtained from the decay tracks). The variables used are the negative four-momentum squared of the photon Q^2, the total $\gamma^* p$ centre of mass energy W, the Bjorken scaling variables x and y, and the square of the four-momentum transfer to the proton t. The absolute value of the latter is very well approximated as the square of the outgoing proton transverse momentum, estimated as the vector sum of the momenta of the ϕ meson and of the scattered positron, computed using the double angle kinematics.

[3] In the H1 coordinate system, the forward ($+z$) direction is that of the outgoing proton beam, and the backward direction is that of the positron beam.

[4] The pseudorapidity η is defined as $\eta = -\ln \tan \theta/2$, where θ is the polar angle with respect to the $+z$ direction.

To remove poorly reconstructed events and to select a region of phase space where the acceptance is well determined and relatively constant as a function of the kinematic variables, the following cuts were also applied to the final sample:

$$\begin{aligned} 6 < Q^2 < 20 \text{ GeV}^2 \\ 0.02 < y < 0.2 \\ |t| \ < 1.0 \text{ GeV}^2. \end{aligned} \tag{2}$$

The y cut is equivalent, to a good approximation, to a cut $42 < W < 134$ GeV/c^2.

3 Cross sections

3.1 *ep* cross section

Fig. 2 shows the invariant K^+K^- mass distribution for the events passing all selection cuts, when the kaon mass is assigned to the detected particles in the central tracking detector. A clear ϕ signal over little background is observed in the mass region $1.00 < m_{K^+K^-} < 1.04$ GeV/c^2, which contains 35 events.

The curve superimposed in Fig. 2 is the result of a fit to a non-relativistic Breit-Wigner distribution (with a width fixed at the PDG value [24]), convoluted with a Gaussian distribution, over a linear background starting at threshold ($m = 2\ m_K$). The fitted mass of the ϕ meson is 1021 ± 2 MeV/c^2, in agreement with the PDG value of 1019.4 MeV/c^2. The r.m.s. of the Gaussian distribution, which reflects the detector resolution, is 6.3 ± 1.4 MeV/c^2, consistent with the resolution of 4.5 MeV/c^2 obtained from a Monte Carlo simulation based on the vector meson dominance model incorporating the detailed description of the detector and of the reconstruction, trigger and event selection procedures [25].

The non ϕ background under the signal in the mass region $1.00 < m_{K^+K^-} < 1.04$ GeV/c^2 is estimated to be $8 \pm 5\%$. The error includes statistical and systematic uncertainties estimated by varying the shape of the background and the limits of the fit. The background due to diffractive vector meson production with proton dissociation was determined for the ϱ mesons to be of $9 \pm 8\%$ of the selected signal, using Monte Carlo simulations cross checked directly on the data [8]. The proton dissociation background is assumed to be the same for the present ϕ sample, for which the limited statistics do not allow detailed checks.

After background subtraction and corrections for efficiencies and acceptances, for QED radiation effects and for the known ϕ decay branching ratio into a kaon pair, the *ep* cross section for elastic ϕ production is

$$\sigma(e + p \rightarrow e + \phi + p) = 26.3 \pm 4.6 \text{ (stat.)} \pm 3.6 \text{ (syst.) pb},$$

integrated over the range $6 < Q^2 \ < 20$ GeV^2 and $42 < W < 134$ GeV/c^2.

3.2 $\gamma^* p$ cross section

The *ep* cross section can be converted into a $\gamma^* p$ cross section using the relation

$$\frac{\mathrm{d}^2\sigma(ep \rightarrow e\phi p)}{\mathrm{d}y\ \mathrm{d}Q^2} = \Gamma\ \sigma(\gamma^* p \rightarrow \phi p), \tag{3}$$

where Γ is a flux factor given, for small values of y, by

$$\Gamma \simeq \frac{\alpha\ (1 - y + y^2/2)}{\pi\ y\ Q^2}. \qquad (4)$$

An integrated flux factor was computed for each of the Q^2 bins considered below, using the Q^2 and W dependences measured in the present data. This procedure leads to additional systematic errors which were included in the quoted results.

The $\gamma^* p$ cross section for ϕ meson elastic production, measured in two Q^2 ranges at an average W value of ≈ 100 GeV/c^2, is

$$\sigma(\gamma^* p \to \phi p) = 9.6 \pm 2.5 \text{ nb} \quad \text{for } Q^2 = 8.3 \text{ GeV}^2$$

and

$$\sigma(\gamma^* p \to \phi p) = 3.1 \pm 0.8 \text{ nb} \quad \text{for } Q^2 = 14.6 \text{ GeV}^2.$$

The quoted errors are the quadratic sums of the statistical and the systematic uncertainties.

These results are presented as a function of W in Fig. 3, together with a compilation of photoproduction and leptoproduction results [10, 11, 12, 16, 17, 18, 27]. The NMC measurements were scaled to the values $Q^2 = 2.1, /8.3$ and 14.6 GeV^2 using their measured Q^2 dependence and the relevant values of the polarisation parameter ε; the ZEUS measurements are performed at Q^2 values very close to ours. The overall normalisation uncertainties of 25 % for the results of Cassel et al. [18], 20 % for NMC [16] and 32 % for ZEUS [17] are not shown on the plot.

The cross section for elastic photoproduction of ϕ mesons shows only a slow rise from the fixed target to the HERA energies, consistent with soft pomeron exchange. In contrast, at high Q^2, the HERA values of the cross sections are observed to be significantly larger than those of the NMC experiment, in spite of the large errors and the fact that the comparison involves two different experiments. The change of behaviour of the cross section with Q^2 and W appears faster for ϕ than for ϱ mesons (compare with [8]).

3.3 t and Q^2 dependences; polarisation

The Q^2 dependence of the total $\gamma^* p$ cross section for elastic ϕ production (see Fig. 4) can be described by a form Q^{-n} with

$$n = 4.0 \pm 1.2 \pm 0.3.$$

The first error is statistical and the second reflects the uncertainty on the background size and shape, and the spread of results according to the details of the fitting procedure. This value is close to that obtained by the NMC Collaboration [16], with $n = 4.5 \pm 0.8$, and by the ZEUS Collaboration [17], with $n = 4.1 \pm 1.2$ (stat.).

Within errors, the Q^2 dependence of ϕ production is thus compatible with that for ϱ ($n = 5.0 \pm 1.0 \pm 0.2$ [8]). It is slightly lower but compatible with a prediction ($n = 6$) obtained for light vector mesons in a non-perturbative model [28], and is compatible with predictions based on a perturbative QCD approach, taking into account the running of α_S and higher order corrections which reduce the prediction of $n = 6$ [14].

An exponential fit of the t distribution for $|t| < 0.5$ GeV^2 gives for the slope the value

$$b = 5.2 \pm 1.6 \text{ (stat.)} \pm 1.0 \text{ (syst.) GeV}^{-2}$$

(see Fig. 5). This result is corrected for the presence of the two backgrounds mentioned above, with fixed relative contributions with respect to the elastic signal and with fixed slopes. The slope of the proton dissociation background is assumed to be $b = 2.5 \pm 1.0$ GeV^{-2}, which is compatible with that measured for ϱ mesons [26] (no dependence of the slope on the proton excitation mass is assumed); the slope for the non-resonant background is taken to be $b = 0.4 \pm 0.4$ GeV^{-2}, as obtained from of fit of the t distribution of the events with $1.05 < m_{K^+K^-} < 1.3$ GeV/c^2 and which do not belong to the ϱ peak ($m_{\pi^+\pi^-} < 0.4$ GeV/c^2). The systematic error includes the effects of varying the amount of each background and its b slope within errors, and those of changing the details of the fitting procedure.

Fig. 6 shows the acceptance corrected distribution of $\cos\theta^*$ for the selected ϕ sample, where θ^* is the angle, in the ϕ meson rest frame, between the direction of the positively charged decay kaon and the line of flight of the ϕ meson (in the $\gamma^* p$ centre of mass system).

This distribution allows the extraction of the parameter r^{04}_{00}, which is the probability for the ϕ meson to be longitudinally polarised. After subtraction of the non-resonant background, which is consistent with being flat in $\cos\theta^*$, and correction for detector effects, the fit to the distribution in Fig. 6 gives

$$r^{04}_{00} = 0.77 \pm 0.11 \pm 0.02.$$

The first error is statistical, the second reflects the uncertainty on the background subtraction. This result is close to that obtained by the ZEUS Collaboration [17]: $r^{04}_{00} = 0.76 \ ^{+0.11}_{-0.16} \pm 0.12$. For ϱ electroproduction, the H1 result [8] is $r^{04}_{00} = 0.73 \pm 0.05 \pm 0.02$. As for ϱ mesons, and in agreement with model predictions [14, 28], the ϕ mesons are thus observed to be dominantly longitudinally polarised.

Assuming s-channel helicity conservation (SCHC), the value of r^{04}_{00} allows in turn the computation of R, the ratio of the longitudinal to transverse photon cross sections. The cross section ratio is found to be

$$R = \sigma_L/\sigma_T \ (\gamma^* p \rightarrow \phi p) = 3.3 \ ^{+4.0}_{-1.4}$$

for $W \approx 100$ GeV/c^2.

4 Cross section ratio $\sigma(\phi)/\sigma(\varrho)$

As mentioned in the introduction, the study of the Q^2 and W evolutions of the ϕ / ϱ cross section ratio for elastic production is of particular interest.

For this measurement, the same selection criteria are used for the two event samples, in order to minimise the systematic effects, which largely cancel in the ratio. Compared to the above, it was also possible to relax the requirements on the positron cluster position and energy deposition in the BEMC, and those concerning the associated BPC hit, since the trigger conditions and the kinematic variable reconstruction are affected in the same way for both samples. The accepted kinematic domain is thus extended to $5 < Q^2 < 25$ GeV^2. A slight difference in the acceptances for the two samples is due to the different opening angles in the laboratory between the two decay hadrons, related to the different phase spaces available.

After acceptance correction and background subtraction from the two samples, following respectively the procedures presented here and in ref. [8], the ϕ to ϱ cross section ratio $R_{\phi/\varrho}$ is measured to be

$$R_{\phi/\varrho} = 0.18 \pm 0.03 \quad \text{for } Q^2 = 6.2 \text{ GeV}^2$$

and

$$R_{\phi/\varrho} = 0.19 \pm 0.05 \quad \text{for } Q^2 = 12.4 \text{ GeV}^2,$$

for $W \approx 100$ GeV/c^2. Fig. 7 presents these results together with the high Q^2 results of the EMC [15], NMC [16] and ZEUS Collaborations [17], and with the ZEUS photoproduction measurement [12].

The present result confirms the significant rise of the cross section ratio with Q^2. The high Q^2 HERA values are indeed close to the SU(3) ratio of 2/9, in contrast with photoproduction results ($R_{\phi/\varrho} \simeq 0.07$). It should be noted again that approaches based on perturbative QCD predict that this value for the ratio should be overpassed at very large Q^2 [14].

There is also an indication that, for comparable Q^2 values, the ratio is higher at HERA than for the fixed target experiments. This is consistent with the observation that the increase of cross sections with energy is faster for ϕ than for ϱ mesons.

5 Conclusion

The cross section for elastic electroproduction of ϕ mesons has been measured at HERA, for $6 < Q^2 \lesssim 25$ GeV^2 and $42 < W < 134$ GeV/c^2. Compared to the fixed target measurement [16], a significant increase of the cross section is observed, contrasting with the evolution in photoproduction; this increase is larger than for ϱ meson electroproduction. The Q^2 dependence of the $\gamma^* p$ cross section is well described in the form Q^{-n} with $n = 4.0 \pm 1.2 \pm 0.3$. The t distribution is parameterised as exponentially falling, with a slope $b = 5.2 \pm 1.6 \pm 1.0$ GeV^{-2}. The elastically produced ϕ mesons are mostly longitudinally polarised and, assuming SCHC, the longitudinal to transverse cross section ratio for virtual photons is measured to be $R = 3.3\,^{+4.0}_{-1.4}$. Finally, the ratio of the cross sections for elastic electroproduction of ϕ and ϱ mesons is measured, for $Q^2 > 5$ GeV^2, to be $R_{\phi/\varrho} = 0.18 \pm 0.03$. This ratio is significantly larger than in photoproduction, and the comparison with fixed target results provides indication that, for comparable Q^2 values, the ratio is higher at HERA than at lower energy.

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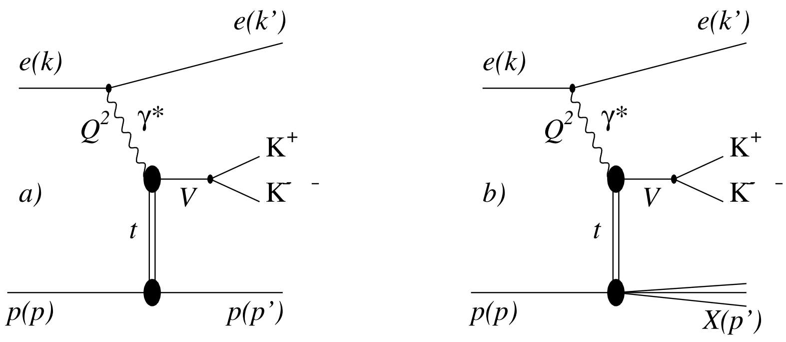

Figure 1: Electroproduction of ϕ mesons: a) elastic scattering; b) proton dissociation.

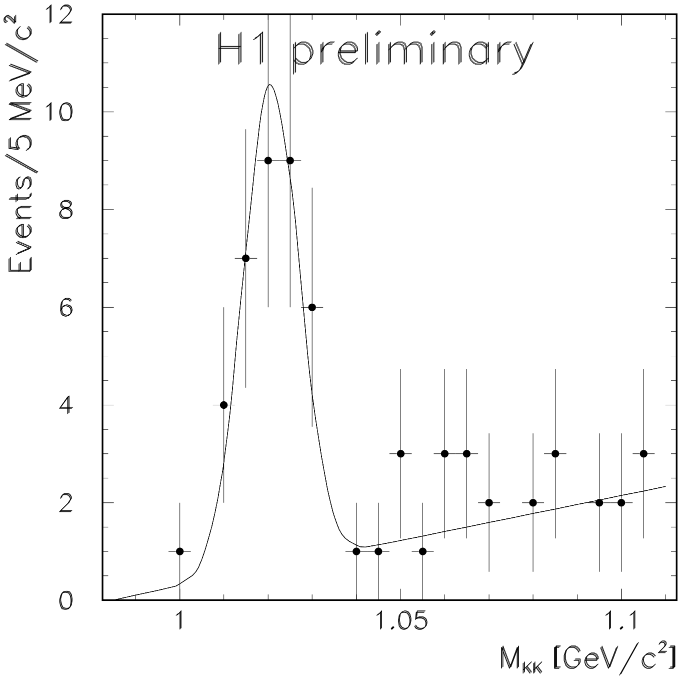

Figure 2: $m_{K^+K^-}$-invariant mass distribution for the selected events; the curve is the result of a fit to a Breit-Wigner distribution convoluted with a Gaussian, over a linear background.

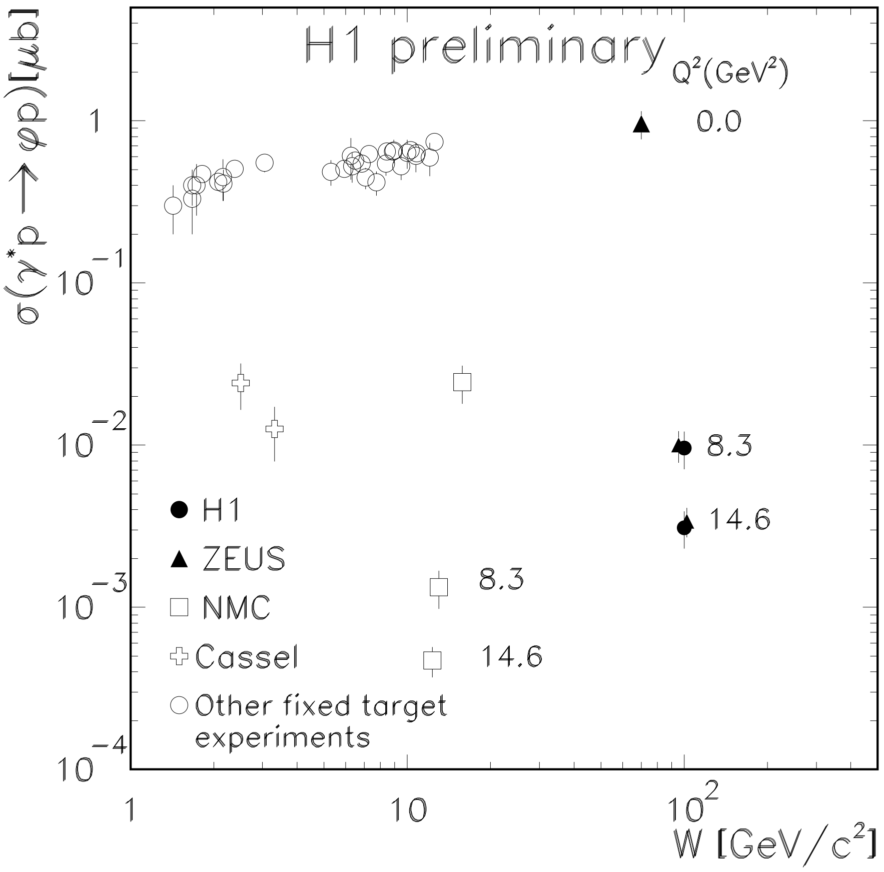

Figure 3: Cross section for $\gamma^* p \rightarrow \phi p$ as a function of W for several values of Q^2. The overall normalisation uncertainties of 25% for the results of Cassel et al., 20% for NMC and 32% for ZEUS are not included. The measurements of Cassel et al. and the lowest Q^2 NMC measurement are for $Q^2 \simeq 2.2$ GeV^2.

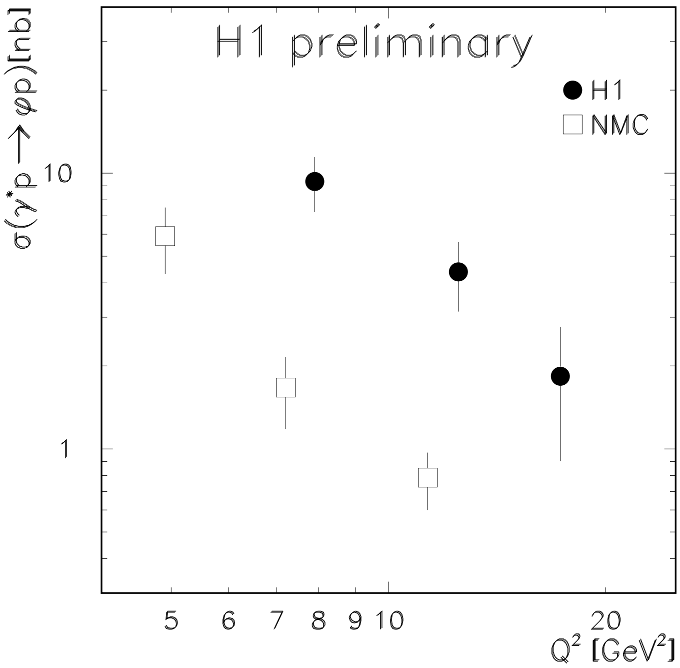

Figure 4: Q^2 dependence of the $\gamma^* p \rightarrow \phi p$ cross section.

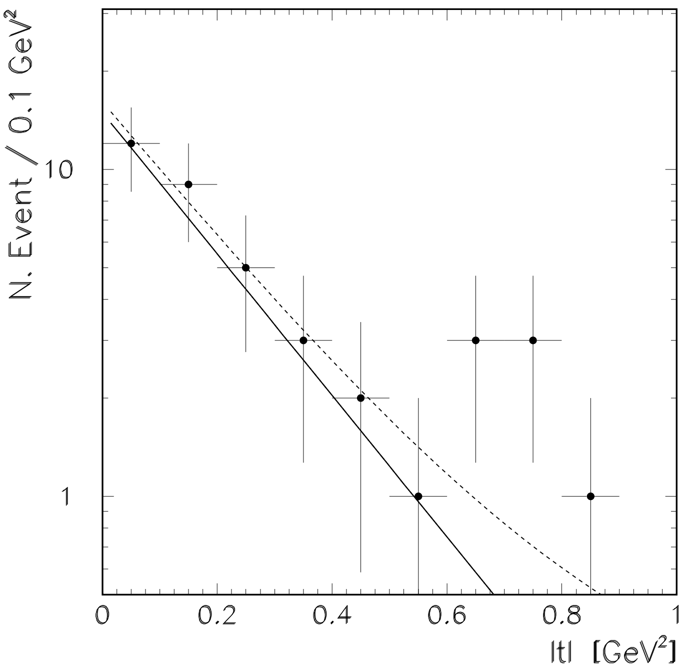

Figure 5: t distribution of the selected events with $1.02 < m_{K^+K^-} < 1.04$ GeV/c^2; the dashed line is a fit including the contributions of the proton dissociation and of the non-resonant backgrounds (see text); the solid line shows the contribution of the elastic ϕ events alone.

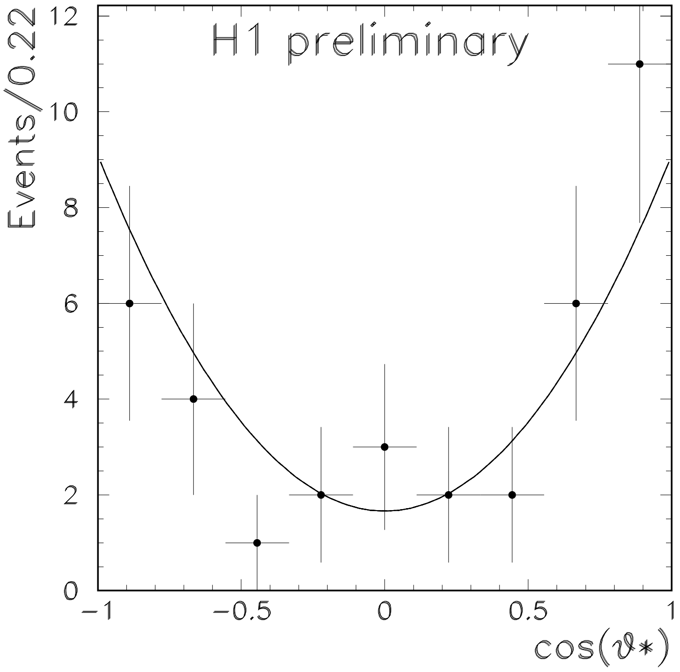

Figure 6: Distribution of $\cos\theta^*$ for the selected ϕ events.

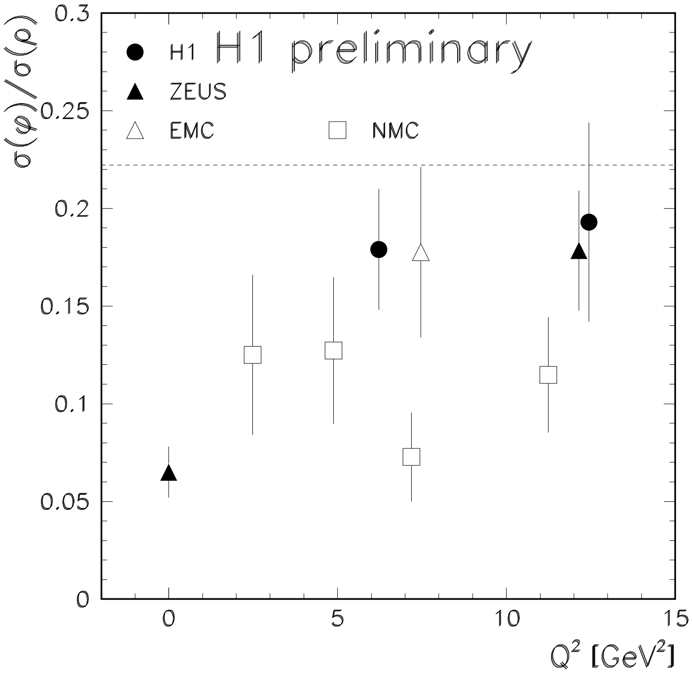

Figure 7: Ratio of the cross sections for elastic ϕ and ϱ production, as a function of Q^2. The dashed line corresponds to the ratio 2/9 from quark charge counting and SU(3).