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Exclusive production of ϕ vector meson during HERA-II

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Abstract

The Hadron Electron Ring Accelerator (HERA) in Germany, which ran from 1992 to 2007, is to date the only high energy electron and proton collider. The ZEUS detector at HERA measured the collisions of 27.5 GeV electrons with 920 GeV protons. Elastic vector meson production was measured during the first phase of HERA (HERA-I) from 1992 to 2000 before HERA was upgraded in 2003 (HERA-II) with increased luminosity. The goal of this project was to analyze data collected during the HERA-II run to identify and quantify the exclusive production of the ϕ vector meson. Runs from the ZEUS experiment were taken from 2005, corresponding to an integrated luminosity of 136 pb^{-1}. The ϕ meson was detected with masses consistent with their theoretical and previously observed invariant masses and the $\gamma^{*}p$ cross section was measured in the kinematic range $5 \leq Q^2 \leq 70 GeV^2$. This is the first time the ϕ vector meson from HERA-II have been studied. Additional analysis to determine systematic errors is necessary to yield information relevant to physics interests. Given that the next highest priority in nuclear physics is the construction of an electron ion collider, resolving as much information from previous measurements at HERA-II will help to guide the research.

1. Introduction

The HERA ep collider vastly expanded the accessible kinematic regions of Deep Inelastic Scattering beyond any previous experiment. At HERA, the proton structure function F_2^p rose unexpectedly as Bjorken variable x decreased, implying a rapid growth of the gluon density at low x. Many processes that could be observed at HERA allowed for the examination of the gluon density in the proton as well as the testing quantum chromodynamics (QCD) [1]. One such process is the exclusive production of vector mesons, such as ϕ, ρ^0, ω, and J/ψ. The production of vector mesons can occur via different processes but the elastic process, $e^- p \rightarrow e^- V p$ where V is any vector meson, is particularly significant for testing and understanding QCD and the gluon density probed at HERA. The process spans both the soft regions describe by models such as Regge theory, as well as the hard region described by perturbative quantum chromodynamics (pQCD). During the HERA-I (1992 – 2000) data taking period, multiple measurements were made of the lighter vector mesons including ϕ [2],[3],[4], focusing on the cross-section dependence due to the four-momentum transfer squared from the virtual photon, Q^2, the center of mass energy of the photon and proton, W, and the four-momentum transfer squared at the proton vertex, t. This paper reports the first examination of the exclusive production of the ϕ vector meson from HERA after the luminosity upgrade to HERA-II. The data sample used was taken with the ZEUS detector for the whole 2005 run and corresponds to an integrated luminosity of 136 pb^{-1}.

This analysis follows the effort made by DESY and the HERA collaborations to preserve the data collected by the detectors past the time of funding. Even though data collection stopped in 2007, funding for HERA did not stop until 2012. In that time, all of the data was uploaded and kept in a usable format for future analyses, given the uniqueness of both the experiment itself and the kinematic region explored. As new colliders specifically the Electron Ion Collider (EIC) are proposed and designed, the data from the HERA collisions provide a wonderful opportunity to guide both physics interests and detector designs. The EIC is the next focus in the field of Nuclear Physics that will rely on the data and measurements made at HERA and hope to further expand upon the observations and conclusions made. In order for the EIC to be most efficient and progress beyond HERA, the data from HERA needs to be thoroughly studied. Otherwise time will be spent during the EIC studying topics and data that could have been done prior to the EIC with data from HERA. Specifically looking at the exclusive production of vector mesons, which there is all of the

HERA-II data yet to be looked at, the process is something that the EIC hopes to study for numerous physics interests of the EIC. After completing the analysis on the data from HERA-II, the final goal is to combine all of the data from both HERA-I and HERA-II on the exclusive production of the ϕ vector meson will decrease the statistical uncertainty on the measurements and either extend the previously studied kinematic regions for this process or understand better how the detector plays a role in studying this process.

This work is based on the data and Monte Carlo data sets preserved as ROOT Ntuples [5], [6] produced by the ZEUS collaboration and used by their kind permission.

2. Theory of Exclusive VM production in DIS

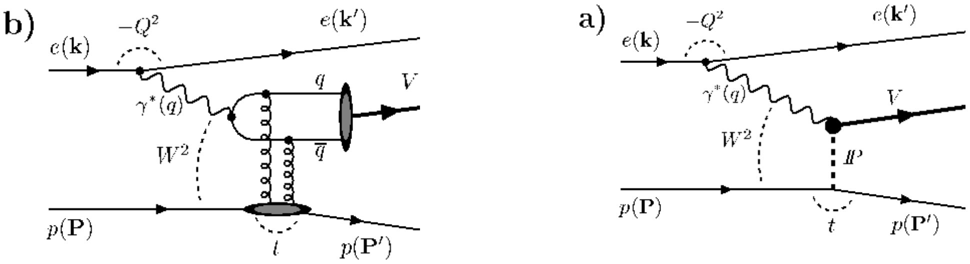

Figure 1. Elastic vector meson production described by (a) perturbative quantum chromodynamics and (b) Regge theory.

The reaction, $e\ p\ \rightarrow e\ V\ p$, can be represented in terms of a series of steps. In models based in pQCD, the electron emits a virtual photon which fluctuates into a quark-antiquark ($q\bar{q}$) dipole. This $q\bar{q}$ pair then interacts with the proton elastically via, to lowest order, the exchange of two gluons. Long after the interaction, the $q\bar{q}$ pair transforms into a vector meson, shown in **Figure 1a**. All vector mesons have a mean half-life between 10^{-22} s and 10^{-24} s, so after the vector meson is formed, it decays almost immediately into decay products that depend on the vector meson. The ϕ vector meson has multiple different decay channels, but the dominant one that provides a clear signal in the detector is the decay into two charged kaons, K^+ and K^-. The exclusive production of vector mesons can also be described via hadronic models such as Regge theory and the Vector Meson Dominance model (VMD), both of which predate QCD. In these models, the virtual photon fluctuates into a vector meson, as described by VMD and the vector meson scatters off the proton via a Pomeron exchange, as described by Regge theory, **Figure 1b**. The choice of which model to use to calculate cross sections is typically dependent upon whether the processes were considered soft or hard. Processes are typically considered to be soft when Q^2 and t are below a few GeV^2 and the mass of the vector meson, M_v produced is also below a few GeV. Hard processes are thought to be best described by pQCD. This is one of the interesting aspects of vector meson production, given their production spans the region of soft and hard processes as Q^2 or t increases, they can hopefully be used to find a link between pQCD and Regge/VDM theory.

Hard processes will occur when at least one of the three variables, Q^2, |t|, and $M_{v,}$ is large. ϕ is a low mass vector meson, unlike J/ψ which is a heavy meson. So any study on J/ψ will typically be focused only in the hard pQCD region whereas ϕ can be used to study both the hard and soft regions, and the transition, depending on Q^2 and |t| [6]. Both of these parameters can be examined in reactions to determine how the cross section changes as a function of one or the other. This is the reason why exclusively studying the vector meson ϕ can be an important probe for testing pQCD.

3. Experimental Set Up

The data was collected from 2005 with the ZEUS detector during HERA-II. The data corresponds to an integrated luminosity of 136 pb^{-1} from $e^- p$ collisions with a proton energy of

920 GeV and electron energy of 27.5 GeV. A detailed description of the ZEUS detector can be found elsewhere [7] but a brief overview of the components relevant to this analysis is given below with the schematic shown in **Figure 2.**

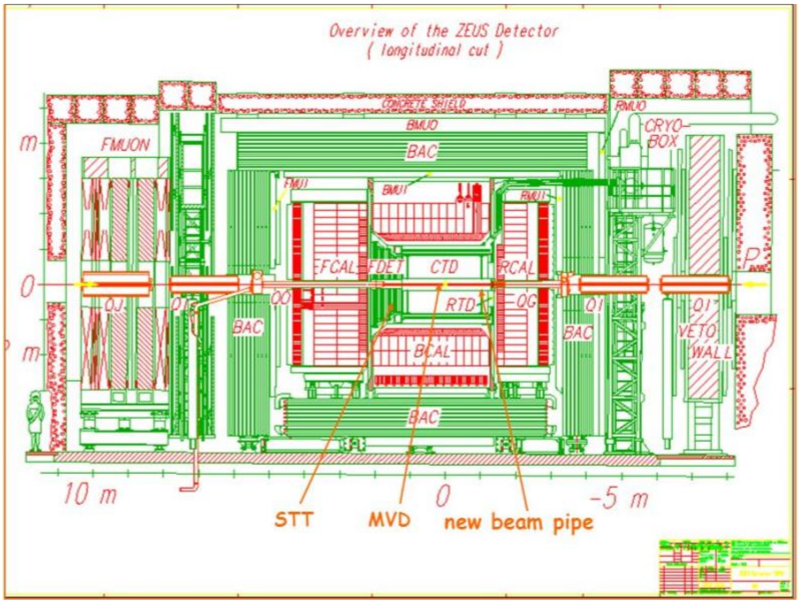

Figure 2. Longitudinal cut of the ZEUS detector at HERA. See Ref. [7] for more details.

Charged particles were reconstructed in the central tracking detector (CTD). The CTD has 72 cylindrical drift chamber layers organized in nine superlayers. The CTD covers the polar angle region $15° < \theta < 164°$. The CTD operates inside a solenoid with a magnetic field of 1.43 T. The transverse momentum resolution for full length tracks is $\sigma(p_T)/p_T = 0.0058 p_T \oplus 0.0065 \oplus 0.0014/p_T$ with p_T in GeV.

The interaction vertices were reconstructed in the silicon micro-vertex detector (MVD). The MVD was installed in the ZEUS detector for the HERA-II running period. The detector is made up of three layers of two back-to-back silicon strip wavers. They provide a resolution of 7.5 μm with a hit efficiency greater than 95%. The MVD covered the polar angle region $10°<\theta<150°$.

The high resolution uranium-scintillator calorimeter (CAL) consists of three parts: the forward (FCAL), the barrel (BCAL), and the rear (RCAL) calorimeters, covering 99.7% of the total solid angle. Each part is subdivided transversely into towers and longitudinally into an electromagnetic section (EMC) and either one (in RCAL) or two (in BCAL and FCAL) hadronic sections. The CAL energy resolutions, measured under test-beam conditions are $\sigma(E)/E = 0.18/\sqrt{E}$ for electrons and $\sigma(E)/E = 0.35/\sqrt{E}$ for hadrons, with E in GeV.

The small angle rear tracking detector (SRTD) has two planes of scintillator strips, attached to the front face of the RCAL, covering the angular region $162° < \theta < 176°$. The SRTD provides a transverse position resolution for the scattered electron of 0.3 cm or angular resolution of 2 mrad.

The hadron electron separator (HES) is installed inside the RCAL. It consists of silicon diodes placed at three radiation lengths longitudinally. The resolution of the electron position in the HES is 0.5 cm, if two adjacent pads are hit by the shower.

The position of the scattered electron was determined by combining information from the CAL, the SRTD and the HES.

The luminosity was measured from the rate of the bremsstrahlung process, $e\,p \rightarrow e\,\gamma\,p$. The photon was measured in a lead-scintillator calorimeter placed in the HERA tunnel at $Z =$ -107 m.

4. Data Selection and Reconstruction

The following kinematic variables were used to describe exclusive ϕ production and its decay into K^+/K^-:

- Four-momenta of incident electron (k), scattered electron (k'), incident proton (P), scattered proton (P') and virtual photon (q)

- $Q^2 = -q^2 = -(k - k')^2$, negative squared four-momentum of virtual photon
- $y = (P \cdot q)/(P \cdot k)$, fraction of energy transferred to the proton in its rest frame
- $s = (k + P)^2$, center of mass energy of electron-proton system
- $x = {Q^2}/{sy}$, the Bjorken variable
- M_{KK} , invariant mass of the two decay kaons
- $W^2 = (q + P)^2$, squared center of mass energy of the photon-proton system

The kinematic variables were reconstructed with the constrained method [8] which does not use the measured energy of the scattered electron, E'_e, since it has the poorest resolution but instead calculates it from the polar angle, θ_e, of the scattered electron, momentum of the ϕ vector meson, p_ϕ, and the polar angle of ϕ, θ_ϕ. The equations to calculate the kinematic variables are given by:

- $E'_e = \left(2E_e - \left(E_\phi - p_\phi \cos(\theta_\phi)\right)/(1 - \cos(\theta_{e'}))\right)$ (1)
- $Q^2 = 2E_e E_{e'}(1 + \cos(\theta_{e'}))$ (2)
- $s = 4E_e E_p$ (3)
- $y \approx \frac{E_\phi - p_\phi \cos(\theta_{e'})}{2E_e}$ (4)
- $W^2 \approx sy$ (5)

The following criteria were applied offline to reconstruct and select the events:

- An electron candidate found using an Artificial Neural Network electron finder with a probability greater than 90%, detected in the RCAL with E'_e >10 GeV.
- The position of the electron was measured using the SRTD, HES, and RCAL. Preference was given to the SRTD, given its superior position resolution, and then HES with RCAL as the last option. The electron had to be detected in a region outside $r = \sqrt{x_e^2 + y_e^2} > 18\ cm$.

- $45 < E - P_z < 65\ GeV$, the summation over the energies and longitudinal momenta of the final state electron and mesons. This cut excludes events with high energy photons radiated in the initial state. The value is expected to peak at twice the electron beam energy of 55 GeV for DIS events.
- The position of the reconstructed vertex was required to be $|Z_{vtx}| < 50cm$.
- Events with two tracks of opposite charge associated with the primary vertex, each with $p_t > 0.15\ GeV$ and pseudorapidity $|\eta| < 1.7$ were selected.
- Events with any energy deposit larger than 300 MeV in the CAL and not associated with the two kaon tracks were rejected.

Events were required to be in the kinematic region $5 < Q^2 < 100\ GeV^2$, 30 < W < 180 GeV and $|t| < 0.6\ GeV^{-2}$.

Monte Carlo Simulation

The track cuts and event selection methods were compared with samples of Monte Carlo (MC) events that were previously generated to match the vertex and detector conditions in ZEUS during 2005. All generated MC events were passed through the ZEUS detector based on GEANT 3 [9]. They were then analyzed using the same exact selection cuts as the data. The process $e\ p \rightarrow e\ \phi\ p$ was modelled using the ZEUSVM MC event generator. The generator is used specifically to model the exclusive production of specific vector mesons with low Q^2 [10].

5. Extraction of ϕ signal

The ϕ signal is an invariant mass of the two kaons, K^+ and K^- which came from the decay of the ϕ, given by

$$M_{K^+K^-} = \sqrt{(E_{K^+} + E_{K^-})^2 - (\vec{p}_{K^+} + \vec{p}_{K^-})^2} \tag{6}$$

with $E_K^2 = M_K^2 + p_K^2$. The background was removed by performing a global fit of a second order polynomial with the signal and then subtracting the background. The signal was fit with a relativistic Breit-Wigner (BW) distribution given by

$$BW(X) \frac{X M_\phi \Gamma_\phi(X)}{\left(X^2 - M_\phi^2\right)^2 + M_\phi^2 \Gamma_\phi^2(X)} \tag{7}$$

$$\Gamma_\phi(X) = \frac{M_\phi}{X} \Gamma_0 \left(\frac{p^*}{p_0}\right)^3, \tag{8}$$

$$p^* = \sqrt{(X/2)^2 - m_K^2}, \tag{9}$$

$$p_0 = \sqrt{\left(M_\phi/2\right)^2 - m_K^2}. \tag{10}$$

The mass of the ϕ vector meson, M_ϕ is 1019.460 ± 0.016 MeV, with a width, Γ_ϕ, of 4.247 ± 0.016 MeV as reported in the Particle Data Group [11]. The mass of a kaon, m_K , is 493.677 ± 0.016 MeV. The expression for the mass distribution fit is given as

$$^{dN}/_{dM_{KK}} = \int BW(M_{KK}) + B(M_{KK}) \tag{11}$$

where $B(M_{KK})$ is the background described by a second order polynomial. Events for exclusive ϕ production were only counted between the region $1.01 < M_{KK} < 1.04\ GeV$.

6. Cross Section Calculation

The ep cross section in each kinematic bin was calculated by

$$\sigma^{ep\rightarrow e\phi p} = \frac{N_{data}}{ABL} \tag{12}$$

where N_{data} is the number of ϕ events in the kinematic bin range, A is the acceptance of the detector, B is the branching ratio for the decay $\phi \rightarrow K^+K^-$ which is 48.9% [11], and L is the luminosity of the data set, 136 pb^{-1}. The total exclusive photon-proton cross section is given by

$$\sigma^{\gamma^* p\rightarrow\phi p}(Q^2, W, t) = \sigma_{MC}^{\gamma^* p\rightarrow\phi p}(Q^2, W, t)\cdot\frac{\sigma_{DATA}^{ep\rightarrow e\phi p}}{\sigma_{MC}^{ep\rightarrow e\phi p}} \tag{13}$$

where the MC is used to correct for the acceptance of the detector and cut efficiencies. $\sigma_{MC}^{\gamma^* p\rightarrow\phi p}$ is calculated by a Regge parameterization which is input into the MC [10]. The statistical uncertainty was calculated for each Q^2 bin. The uncertainty in the number of events for each bin was calculated by $\sqrt{N_{data}(Q^2)}$, assuming a Poisson distribution, and the each value was scaled by the factors in equations (12) and (13).

7. Results & Discussion

The invariant mass distribution of ϕ was extracted from the MC files, to verify the accuracy of the analysis as shown in **Figure 2**. The invariant mass distribution from the ZEUS data, for ϕ with the corresponding fit function after event selection is shown in **Figure 3a**. The extracted invariant mass distribution for the K^+K^- pairs is shown in **Figure 3b**. A total of 1192 ϕ candidates were found under the distribution. The invariant mass of the M_{KK} distribution is $M_{KK} = 1.0194 \pm 0.0001$ GeV with the width of the resonance, $\Gamma_{KK}=0.0065 \pm 0.0003$ GeV.

The analysis did not consider effects of any online event selection. During collection of data, certain triggers can be enabled to only collect data with certain parameters. For more precise analysis, determining the trigger information for each event is necessary since certain triggers such as scattered electron position or detection of a scattered proton can bias the data. The inability to use trigger cuts that are typically used for vector meson analyses was due to missing information that possibly did not get preserved and require additional time to find.

Previous analyses on these vector mesons required additional steps to remove specific background sources interfering with the mass distributions. The major background source for the light vector mesons such as ϕ is proton dissociation, described by $e\ p\ \rightarrow e\ V\ X$, where X represents the remnants and products produced in breaking up the proton. This will be examined in the next step of the analysis and can be addressed in further analysis on the data set by using a combination of different MC generators such as EPSOFT and PYTHIA for proton dissociative events.

The cross section was calculated as a function of Q^2 with a total range between 5 GeV^2 and 100 GeV^2 as shown in **Table 1** and **Figure 5**. The error bars reported for the cross section measurements are calculated from the statistical uncertainty from the number of events per Q^2 bin. The measured cross section as a function of Q^2 in this study, matched previous measurements very well except for the low Q^2 bin between 5 and 8 GeV^2. The previous measurements included two other analyses carried out with the ZEUS detector during HERA-I as well as measurements made in the H1 detector at HERA-II, a 4π detector similar to ZEUS. Both detectors during HERA-I were able to make low Q^2 measurements. There were changes made to the ZEUS detector before the HERA-II run with the placement of a micro vertex detector surrounding the beamline. This detector provided high precision measurements of interaction vertices but prevented the measurement of the scattered electron at a radius outward from the beamline less than 18 cm. This led to a $Q^2 > 5$ GeV^2 cut for HERA-II but a $Q^2 > 2$ GeV^2 was made for the HERA-I measurements. It is likely that the electron position cut at 18 cm is removing low Q^2 events which is reducing the cross section in that bin. This is clear from the number of events between 5 and 8 GeV^2 which are much lower than the number of events between 8 and 11 GeV^2. This is not supposed to be the case since the exclusive production of ϕ is greatest at lower Q^2 values. This issue at low Q^2 provides an indication of the importance to the detector geometry. For future colliders and detectors, such as the EIC, if studying the exclusive vector meson process is important, it will be necessary to construct the detector in a fashion that low angle scattered electrons can be detected.

This analysis will be continued with future work including the calculation of additional cross sections, calculation of systematic errors and performing the analysis with all the data from HERA-II (2003 to 2007) and HERA-I. Previous analysis on the ϕ vector meson included cross sections as a function of both Q^2 and W, W and |t|, and a number of other kinematic variables [8]. To really understand this process, additional cross sections as a function of multiple variables is necessary. The next step in the analysis is the calculation of systematic errors arising from each of the cuts made to retrieve the data. It involves adjusting specific cuts by small amounts determined by the resolution related to each cut and determining how changes in the cuts affect the measured cross section. Usually the systematic errors are larger than the statistical errors and are reported together. Once the additional cross section analysis is complete and systematics are calculated it would be worthwhile to perform the analysis on all of the data collected by the ZEUS detector during both HERA-I and HERA-II. One of the most interesting features regarding the cross section of exclusive vector meson production is the dependence on Q^2, x, W and |t|. There are both Regge/VMD theory and pQCD models that predict the cross section dependence as a function of these kinematic variables although a high degree of uncertainty remains in these calculations. Previous calculations were done during HERA-I where the total integrated luminosity over the three years was approximately 66.4 pb^{-1}. The upgrade to HERA-II led to an additional 400 pb^{-1} over the course of only four years [6]. Conducting the analysis on all of the data collected at HERA including both HERA-II and HERA-I, will allow for better resolution, and better kinematic coverage over previous measurements to shed light on some of the currently unknown aspects of exclusive vector meson production. The low Q^2 cut at 5 GeV^2 during HERA-II in the ZEUS detector could diminish the number of events measured considering that the number of events observed during HERA-I with only 66.4 pb^{-1} was 3600 events [8] while the 2005 data set, corresponding to 136 pb^{-1}, only detected 1200 events. The inability to measure effectively below 8 GeV^2 significantly reduces the number of detected events. It is possible that all of the data from HERA-II will only double the number of ϕ events observed which is much lower than previously expected without accounting for the HERA-II large electron position cut. But even still doubling the number of observed events might still be enough of an increase to shed light on some current uncertainties regarding the exclusive production of the ϕ vector meson.

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$Q^2\ Bin\ [GeV^2]$	$\langle Q^2 + M_\phi^2 \rangle\ [GeV^2]$	Events	$\sigma_{Tot}^{\gamma^* p \to \phi p}\ [nb]$
6-8	8.4	35 ± 10	8.36 ± 5.4
8-11	10.7	393 ± 27	8.90 ± 0.6
11-15	13.8	436 ± 27	5.20 ± 0.3
15-20	18.1	214 ± 19	2.59 ± 0.2
20-30	24.5	114 ± 14	1.20 ± 0.15
30-70	40.5	26 ± 7	0.36 ± 0.10

Table 1. The $\gamma^* p \to \phi p$ cross section, $\sigma_{Tot}^{\gamma^* p \to \phi p}$, as a function of $Q^2 + M_\phi^2$ with W = 75 GeV. The number of events were determined from the number of events under the Breit-Wigner distribution after subtraction of the background.

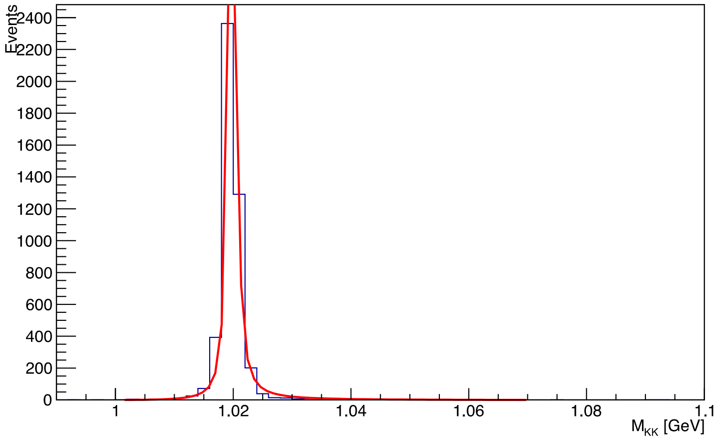

Figure 3. Invariant mass distribution of K^+K^- candidate pairs for ϕ meson from Monte Carlo simulation using the ZEUSVM event generator. There was no background in the MC which is expected with proper set of cuts and parameters.

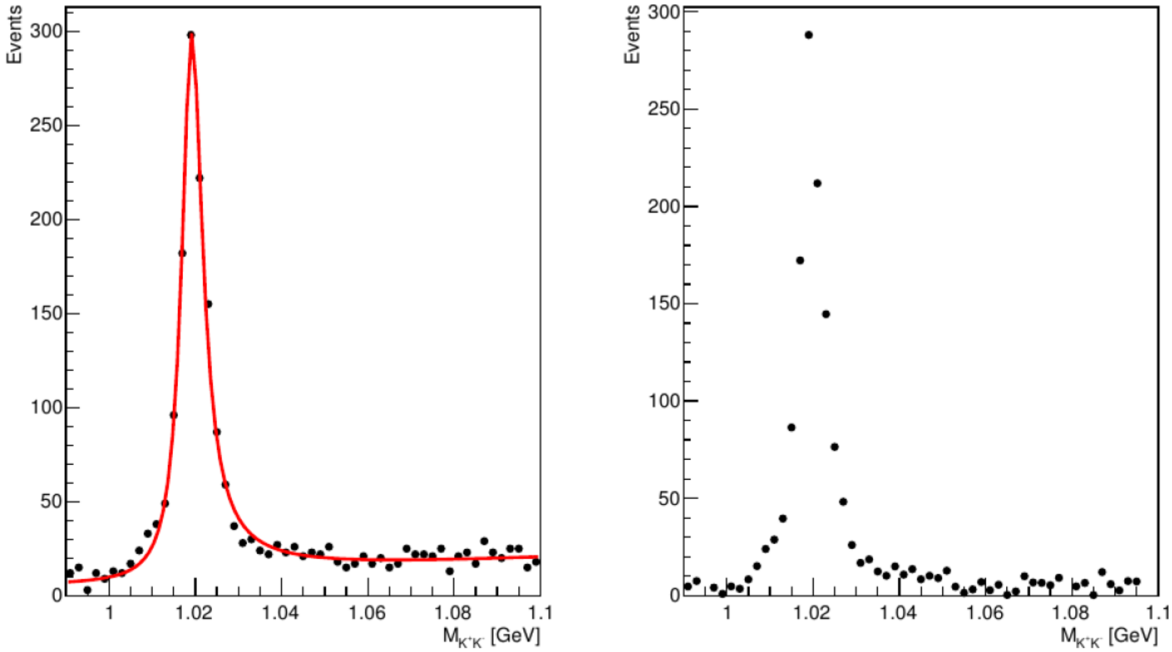

Figure 4. (a) Background and signal for the ϕ meson. The signal was fit with a relativistic Breit-Wigner and a second order polynomial for the background. (b) The remaining signal after subtraction of the background.

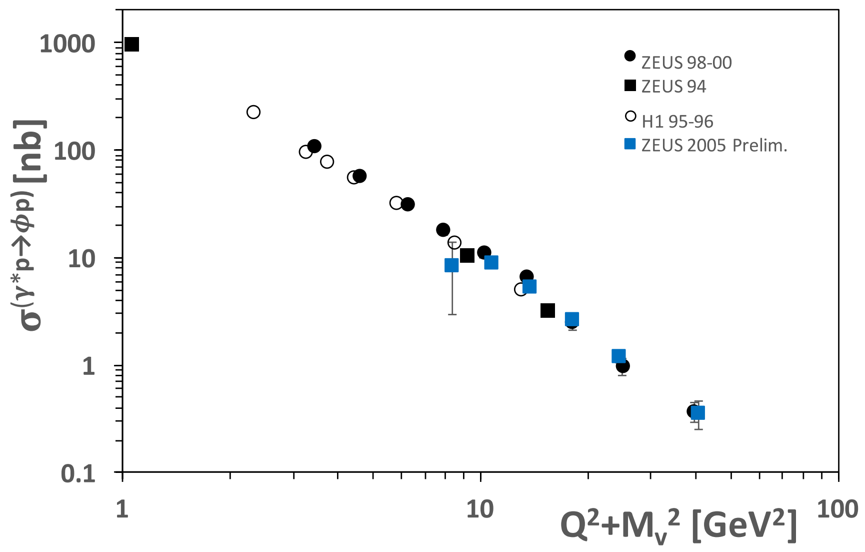

Figure 5. The $\gamma^{*}p \rightarrow \phi p$ cross section for the exclusive production of the ϕ vector meson. The cross section is a function of $Q^2 + M_{\phi}^{2}$ for W=75 GeV. The cross section measured in this study (ZEUS 2005 Prelim.) was compared to previous measurements [1],[2],[3]. The error bars reported are statistical uncertainties calculated from $\sqrt{N}$ in each bin range.