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Extraction of the Pomeron Trajectory from a Global Fit to Exclusive ρ^0 Meson Photoproduction Data

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H1 Collaboration

Abstract

Based on data on elastic ρ^0 photoproduction from the H1, Omega and ZEUS collaborations, a fit has been performed to extract the value $\alpha_{\mathbb{P}}(t)$ of the pomeron trajectory at fixed values of t from the W dependence of the differential γp cross section $\mathrm{d}\sigma_{\gamma p}(W)/\mathrm{d}t$. The data used in the fit cover the range of $8.3 \leq W \leq 94\,\mathrm{GeV}$ in γp centre-of-mass energy and $0.01 \leq |t| \leq 0.95\,\mathrm{GeV}^2$ in momentum transfer.

A linear fit to the resulting values of $\alpha_{\mathbb{P}}(t)$ yields $\alpha_{\mathbb{P},0} = 1.0871 \pm 0.0026(stat.) \pm 0.0030(syst.)$ for the intercept and $\alpha'_{\mathbb{P}} = 0.126 \pm 0.013(stat.) \pm 0.012(syst.)\,\mathrm{GeV}^{-2}$ for the slope of the pomeron trajectory.

The data are also compatible with the Donnachie-Landshoff trajectory $\alpha_{\mathbb{P}}(t) = 1.0808 + 0.25\,\mathrm{GeV}^{-2} \cdot t$ at low values $|t| \lesssim 0.3\,\mathrm{GeV}^2$ and a constant value of $\alpha_{\mathbb{P}}(t)$ at larger values of $|t|$.

1 Introduction

The exclusive photoproduction of ρ^0 mesons $\gamma p \to \rho^0 p$ has been studied in great detail over the last 40 years [1, 2, 3, 4, 5, 6, 7, 8]. This process shows the typical characteristics of a diffractive reaction, i.e. a weak increase of the cross section with the photon-proton centre-of-mass energy W and an exponential decrease as function of the modulus of the squared momentum transfer $|t|$.

This behaviour can be understood in terms of the vectormeson dominance model (VDM) [9], where the hadronic part of the photon wavefunction is conceived as a superposition of vector–meson states, in which the contribution from the ρ^0 dominates. This hadronic component of the photon may then participate in hadron–hadron interactions, notably in elastic scattering off the proton.

Thus, an understanding of ρ^0 photoproduction sheds light on the hadronic properties of the photon, including the total photon–proton cross section, which is linked to the elastic scattering amplitude by the optical theorem.

At sufficiently high centre-of-mass energies W, elastic hadron-hadron scattering is well described by the exchange of a single Regge trajectory [10], the Pomeron [11], while at lower values of W the exchange of additional meson trajectories becomes important. The contribution of the exchange of these so-called subleading trajectories to the production cross section is often summed up by introducing an effective Regge trajectory, the Reggeon.

In this high–W region, where Pomeron exchange is dominant, the energy dependence of elastic ρ^0 photoproduction at fixed momentum transfer t is in diffractive models directly linked to the Pomeron trajectory $\alpha_{\mathbb{P}}(t)$ by

$$\frac{\mathrm{d}\sigma_{\gamma\mathrm{p}}(W)}{\mathrm{d}t} \propto \left(\frac{W}{W_0}\right)^{4(\alpha_{\mathbb{P}}(t)-1)} .$$

Thus, a measurement of the W dependence of elastic ρ^0 photoproduction in bins of t is determines the Pomeron trajectory $\alpha_{\mathbb{P}}(t)$, which is often approximated by a linear function $\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P},0} + \alpha'_{\mathbb{P}} \cdot t$.

The ZEUS collaboration has measured ρ^0 photoproduction cross sections [7] at high values of $W \approx 94\,\mathrm{GeV}$, and has combined their data with data taken at lower energies [2] and with earlier HERA data from H1 [4] and ZEUS [3, 6] in order to extract the W dependence of ρ^0 photoproduction and thus the Pomeron trajectory. Their result is $\alpha_{\mathbb{P}}(t) = (1.096 \pm 0.021) + (0.125 \pm 0.038)\,\mathrm{GeV}^{-2} \cdot t$. The intercept $\alpha_{\mathbb{P},0}$ is consistent with the expectations of Donnachie and Landshoff [12] ($\alpha_{\mathbb{P},0} = 1.0808$) and Cudell [13] ($\alpha_{\mathbb{P},0} = 1.096^{+0.012}_{-0.009}$), whereas the measured slope $\alpha'_{\mathbb{P}}$ is significantly lower than the canonical value of $\alpha'_{\mathbb{P}} = 0.25\,\mathrm{GeV}^{-2}$ extracted from other diffractive processes [14].

In the present analysis, we combine a global fit the new H1 measurements [8] with earlier measurements ofthe H1 [4], Omega [2] and the ZEUS collaborations [3, 6, 7] in order to achieve the best possible accuracy for the determination of the Pomeron trajectory.

Various cross section definitions for rho^0 production are used in the literature; we adopt a definition where the resonant part of the dipion mass spectrum is integrated in the region

$2m_\pi < m_{\pi\pi} < m_\rho + 5\Gamma_{\rho,0}$, with the value of $m_\rho + 5\Gamma_{\rho,0} = 1.52\,\mathrm{GeV}$. For data sets which use a different cross section definition, in particular if the integral extends over a different mass range, correction factors have been applied.

2 Input Data Sets

2.1 The Omega Data Set

In 1982, the Omega collaboration published [2] measurements of elastic ρ^0 photoproduction at a tagged photon beam (experiment WA4) at CERN. The measurements were performed in the kinematic range $0.06 < |t| < 1\,\mathrm{GeV}^2$ in three bins of photon energy E_γ, i.e. $20 < E_\gamma < 30\,\mathrm{GeV}$, $30 < E_\gamma < 45\,\mathrm{GeV}$, and $45 < E_\gamma < 70\,\mathrm{GeV}$, corresponding to γp centre-of-mass energies of 6.8, 8.3, and $10.3\,\mathrm{GeV}$, respectively. The measurements were restricted to the dipion mass range $0.56 < m_{\pi\pi} < 0.92\,\mathrm{GeV}$.

The t spectra were measured in 47 bins of $0.02\,\mathrm{GeV}^2$ width. Figure 3 of the publication presents the t spectra in terms of numbers of events after acceptance correction, together with a fit of the form $\mathrm{d}\sigma/\mathrm{d}t = a \cdot \exp(bt + ct^2)$. Unfortunately, no table of the original cross sections with their errors was published, only the result of the fits.

In order to include the data into the fit, the original event numbers were extracted from Figure 3 of the paper. It was verified that a fit to these data yields values and errors for the parameters b and c that are identical to the published ones. The factor between number of events and the differential cross section per bin was determined from the published t-integrated cross sections (Table 2 of the paper), such that the integral of the fitted differential cross section in the range $0 < |t| < 1\,\mathrm{GeV}^2$ reproduces the published integrated cross section as obtained from a fit using the skewed relativistic Breit-Wigner line shape (Hypothesis (3) in the Table) as proposed by Ross and Stodolsky [15].

It turned out to be necessary to scale up the statistical errors by a factor of $\sqrt{\chi^2/n.d.f.}$ in order to obtain reasonable χ^2 values of the fits.

An additional correction factor of 1.187 ± 0.051 was applied in ordecr to correct the cross section to the full dipion mass range of $2m_\pi < m_{\pi\pi} < m_\rho + 5\Gamma_{\rho,0}$, with the value of $m_\rho + 5\Gamma_{\rho,0} = 1.52\,\mathrm{GeV}$, which is the cross section definition adopted in this analysis. The error of the correction factor is due to a variation of the skewing parameter n in the region $1 < n < 4$, which is the range of values observed by the Omega collaboration. The error of $4.3\,\%$ is treated as a systematic error; it is assumed to be uncorrelated because it is known that the skewing parameter changes with t.

Finally, the data points were grouped according to the t binning used for the global fit, corrected to the bin centre in t according to the t dependence given by the Omega collaboration, and averaged. It was verified that a fit of the t dependence to the rebinned data points yields results that are compatible with fits to the original data, in terms of the values of the fit parameters and of their errors.

A global normalization error, which is assumed to be fully correlated for all data points in a given photon energy interval, is derived from the uncertainty of the integrated cross section as given by the Omega collaboration.

2.2 The H1 Data Sets

The H1 HERA-1 Measurement

The H1 Collaboration has measured elastic ρ^0 photoproduction [4] for $0 < |t| < 0.5\,\mathrm{GeV}^2$ at a mean $\langle W \rangle = 55\,\mathrm{GeV}$ using data taken in 1993. Of the systematic errors listed in Tab. 4 of the paper, the errors from the track fit efficiency, resonance extraction and luminosity as well as half of the error from the trigger efficiency were taken as normalization uncertainty of $17\,\%$, while the rest of the errors are treated as uncorrelated, amounting to $22\,\%$.

The data points were corrected for the t slope according to the measured t dependence and averaged where appropriate, treating the systematic error of the averaged data points as fully correlated.

The Preliminary H1 HERA-2 Measurement

Based on data taken in 2005, the H1 collaboration has released preliminary data [8], covering the range of $W = 20 - 90\,\mathrm{GeV}$ and $0 < |t| < 0.7\,\mathrm{GeV}^2$ for the measurement of the elastic cross section; 60 cross section values have been measured in eight bins of t, with ten bins in W for $|t| < 0.1\,\mathrm{GeV}^2$ and five at larger values of $|t|$. Ten sources of correlated errors, as described in [8], are taken into account. The normalization uncertainty of this data set amounts to $5.3\,\%$.

These data are sufficient to determine $\alpha_{\mathbb{P}}(t)$ with high accuracy for $|t| < 0.4\,\mathrm{GeV}^2$.

2.3 The ZEUS Data Sets

The ZEUS LPS Measurement

The ZEUS collaboration has used their Leading Proton Spectrometer (LPS) in a measurement of elastic ρ photoproduction [5] using data taken in 1994. Four data points with t values in the range $0.073 < |t| < 0.40\,\mathrm{GeV}^2$ were published. The measurement covered a range in photon-proton centre-of-mass energy of $50 < W < 100\,\mathrm{GeV}$, with a mean $\langle W \rangle = 73\,\mathrm{GeV}$.

From the list of systematic uncertainties published, we treat the errors from the luminosity, sensitivity to the proton beam angle, cross section extraction, radiative corrections and ω and ϕ background as fully correlated, corresponding to an overall normalization error of $6\,\%$; the rest of the errors is treated as an uncorrelated error of $11\,\%$.

The published differential cross section values were corrected to the nearest t bin centre according to the t-dependence observed by ZEUS, using an exponential t-dependence $\exp(bt)$ with $b = 9.8 \pm 0.8(stat) \pm 1.1(syst)\,GeV^{-2}$. The error from this “swimming” of the data points was evaluated and is treated as a correlated systematic error.

The data points were also corrected from the mass range $0.55 < m_{\pi\pi} < 1.2\,\mathrm{GeV}$ used in the publication to the full mass range as described above; the correction factor amounts to 1.09. Since the published data are already corrected for skewing effects, no additional uncertainty arises here.

The ZEUS Low-$|t|$ Measurement

Using data taken from the year 1994, the ZEUS collaboration has performed a measurement of elastic ρ photoproduction [6] in the region $|t| < 0.5\,\mathrm{GeV}$ and $50 < W < 100\,\mathrm{GeV}$, at a mean value of $\langle W \rangle = 71.7\,\mathrm{GeV}$. Differential cross sections were measured at twelve values bins of t.

We have averaged the first three t bins and the fourth and fifth t bin and corrected the measurements to the t binning chosen for this global fit, using the published t dependence.

The systematic errors from the luminosity measurement, the cross section extraction and the radiative corrections were assumed to be correlated, resulting in a $5\,\%$ normalization uncertainty, the rest of the systematic errors are treated as uncorrelated and amount to $10\,\%$.

The ZEUS High-$|t|$ Measurement

Based on a data set taken in 1995, the ZEUS collaboration has performed a third measurement of elastic ρ^0 photoproduction [7], covering the range $0.35 < |t| < 1.62\,\mathrm{GeV}^2$.

The seven data points in the range $0.35 < |t| < 1.0\,\mathrm{GeV}^2$ were transferred to the common t bin centres of this global analysis if neccessary, using the published t dependence.

A global normalization uncertainty of $15\,\%$ and the published values for the other systematic errors were taken into account; the uncertainty arising from the subtraction of proton dissociation background was considered as a correlated error.

3 Fit Procedure

The differential γp cross sections measured at a particular value of $t = t_{\mathrm{j}}$ are fitted by the function

$$\frac{\mathrm{d}\sigma^{\gamma\mathrm{p}}(W)}{\mathrm{d}t} = s_{\mathrm{j}} \left(\frac{W_{\mathrm{i}}}{W_0}\right)^{4(\alpha_{\mathrm{j}}-1)} = f_{\mathrm{i}}, \tag{1}$$

with $W_0 = 40\,\mathrm{GeV}$. The parameter α_{j} is, for elastic ρ^0 production, the value of the pomeron trajectory $\alpha_{\mathrm{j}} = \alpha_{\mathbb{P}}(t_{\mathrm{j}})$, and $s_{\mathrm{j}} = \frac{\mathrm{d}\sigma^{\gamma\mathrm{p}}(W_0,t_{\mathrm{j}})}{\mathrm{d}t}$ is the differential cross section at the respective value of t.

The fit minimizes the expression

$$\chi^2 = \sum_i \frac{(m_{\mathrm{i}} + \sum_{\mathrm{k}} \sigma_{\mathrm{ik}} b_{\mathrm{k}} - f_{\mathrm{i}})^2}{\sigma_{\mathrm{i}}^2} + \sum_{\mathrm{k}} b_{\mathrm{k}}^2$$

where m_{i} denotes the measured values, σ_{i} the statistical and uncorrelated systematic errors added in quadrature, σ_{ik} are the signed coefficients for systematic errors, $f_{\mathrm{i}}(a_{\mathrm{j}}) = f(a_{\mathrm{j}}, W_{\mathrm{i}}, t_{\mathrm{i}})$ are the fit function values evaluated at the W and t value of the respective measurement. The fit result are the function parameters a_{j} and the coefficients b_{k} which represent the best shifts of the various systematic error sources. This approach is similar to the method employed in the averaging of inclusive F_2 data [16].

Altogether 26 parameters a_{j} are determined, corresponding to the normalization and the W exponent in each of the 13 t bins, plus 19 coefficients b_{k} for the correlated error sources.

It is important to note that the global fit is not based on any assumption about the t dependence, i.e. the form factor, of the cross section, but that for each t bin the normalization s_{i} and the W exponent α_{i} are determined individually.

However, because the fit includes all data points together, correlated error sources lead to correlations between the resulting fit parameters across different t bins.

Correlated and uncorrelated errors are fully propagated in this fit, so that the full covariance matrix is obtained for the resulting values $\alpha_{\mathbb{P}}\left(t_{\mathrm{i}}\right)$.

Using the values $\alpha_{\mathbb{P}}\left(t_{\mathrm{i}}\right)$ obtained from the fit to the data and their covariance matrix, it is possible to perform a straight line fit to obtain the intercept $\alpha_{\mathbb{P},0}$ and slope $\alpha'_{\mathbb{P}}$ of the pomeron trajectory. The χ^2 of this fit may serve as an indication whether such a straight line is able to describe the data in a satisfactory way.

4 Results

Fig. 1 shows the result of the global fit in all 13 t bins.

The overall quality of the fit is satisfactory, with a $\chi^2 = 111.7$ for $d.f. = 80$ degrees of freedom (106 data points enter the fit, and 26 free parameters are determined).

All data sets contribute a reasonable amount to the total χ^2. However, it is clearly visible that the Omega data at $W = 8.3\,\mathrm{GeV}$ lie systematically above the fit for $|t| < 0.6\,\mathrm{GeV}^2$, which leads to a best value for the normalization of this data set that is significantly shifted; the shift is, however, less than 3 standard deviations.

Since correlated uncertainties, in particular the normalizations, of all data sets are treated consistently across the whole t range, the high precision of the various data sets at low $|t|$, in particular the H1 data from 2005, constrains the normalization of all data sets; this leads to a reduced uncertainty from the correlated errors also at larger values of $|t|$, where the same data is used as in the previous analysis [7] by the ZEUS collaboration.

Fig. 2 shows the fitted values $\alpha_{\mathbb{P}}\left(t\right)$ as a function of t. The values are in excellent agreement with the values obtained from H1 data alone [8] and with those obtained by the ZEUS collaboration from a combined fit to the Omega, ZEUS, and ’93 H1 data [7].

However, while the values obtained by ZEUS are in perfect agreement with a linear pomeron trajectory of the form $\alpha_{\mathbb{P}}\left(t\right) = \alpha_{\mathbb{P},0} + \alpha'_{\mathbb{P}} \cdot t$, which has a significantly shallower slope $\alpha'_{\mathbb{P}} = 0.125 \pm 0.038)\,\mathrm{GeV}^{-2}$ than the canonical value [14] $\alpha'_{\mathbb{P}} = 0.25\,\mathrm{GeV}^{-2}$ for the soft pomeron, the new result shows with increased precision that at low values of $|t| \lesssim 0.3\,\mathrm{GeV}^2$ the data are in very good agreement with the slope of $0.25\,\mathrm{GeV}^{-2}$. At larger values $|t| \gtrsim 0.5\,\mathrm{GeV}^2$, the significant difference between the data and the Donnachie-Landshoff soft pomeron trajectory found by ZEUS is confirmed; the data are even compatible with a constant value of $\alpha_{\mathbb{P}} \approx 1.00 \pm 0.03$ in this region.

These observations are in broad agreement with the indications from UA8 data [17] that the pomeron trajectory flattens at large $|t|$. It is interesting to note that also models based on gauge–string duality [18] predict that the pomeron trajectory flattens at large $|t|$.

A straight line fit fit to the observed $\alpha_{\mathbb{P}}$ values, as shown in Fig. 3, yields for the Pomeron trajectory

$$\alpha_{\mathbb{P}}(t) = 1.0871 \pm 0.0026(stat.) \pm 0.0030(syst.) + (0.126 \pm 0.013(stat.) \pm 0.012(syst.))\,\mathrm{GeV}^{-2} \cdot t$$

with a correlation coefficient of 0.37 between $\alpha_{\mathbb{P},0}$ and $\alpha'_{\mathbb{P}}$. This result is in excellent agreement with the measurement from the ZEUS collaboration [7], i.e.

$$\alpha_{\mathbb{P}}(t) = 1.096 \pm 0.021 + (0.125 \pm 0.038)\,\mathrm{GeV}^{-2} \cdot t$$

and the measurement using H1 data alone [8]

$$\alpha_{\mathbb{P}}(t) = 1.093 \pm 0.003(stat.)^{+0.008}_{-0.007}(syst.) + (0.116 \pm 0.027(stat.)^{+0.036}_{-0.046}(syst.))\,\mathrm{GeV}^{-2} \cdot t.$$

This linear fit has a reasonable overall $\chi^2/d.f. = 14.7/11$, therefore the hypothesis of a linear pomeron trajectory in the range $0 < |t| < 1\,\mathrm{GeV}^2$ cannot be excluded.

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H1 PRELIMINARY

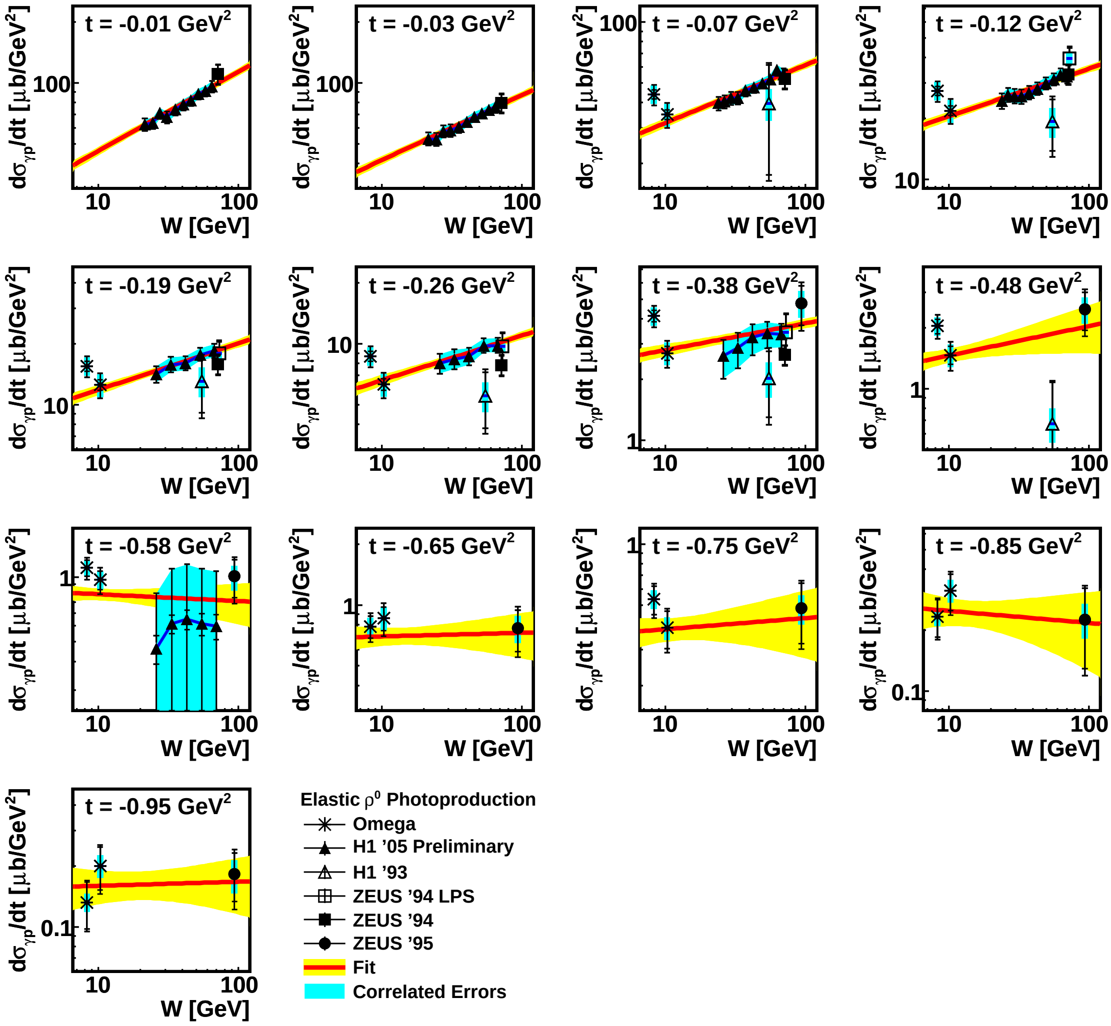

Figure 1: The fit of the form $\mathrm{d}\sigma/\mathrm{d}t(\gamma p \to \rho^0 p) = s_{\mathrm{i}}(W/W_0)^{4(\alpha_{\mathrm{i}}-1)}$ with $W_0 = 40\,\mathrm{GeV}$ to the elastic ρ^0 photoproduction cross section data from the Omega [2], H1 [4, 8] and ZEUS [5, 6, 7] collaborations. For the data points, the inner error bars represent the statistical and uncorrelated systematic error, the outer error bars the full error; the shaded band indicates the size of the correlated errors of each data set.
The global fit has a $\chi^2/d.f. = 111.7/80$.

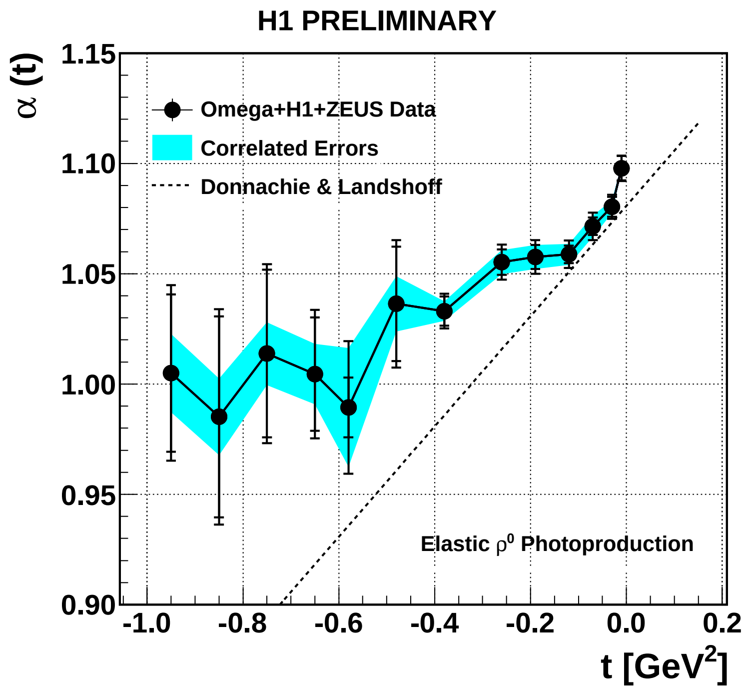

Figure 2: The result of the fit shown in Fig. 1. The coefficients $\alpha_{\mathrm{i}} = \alpha_{\mathbb{P}}(t_{\mathrm{i}})$ are shown as a function of the momentum transfer t.
For each bin in t, separate coefficients s_{i} and α_{i} are fitted. The correlations of the data points between different t bins are taken into account and lead to correlations between the fitted coefficients.
The inner error bars represent the statistical and uncorrelated systematic error, the outer error bars the full error; the shaded band indicates the size of the correlated errors of each data set.
The pomeron trajectory $\alpha_{\mathbb{P}}(t) = 1.0808 + 0.25 \cdot t$ with the parameters from Donnachie and Landshoff [14, 12] is shown as dashed line.

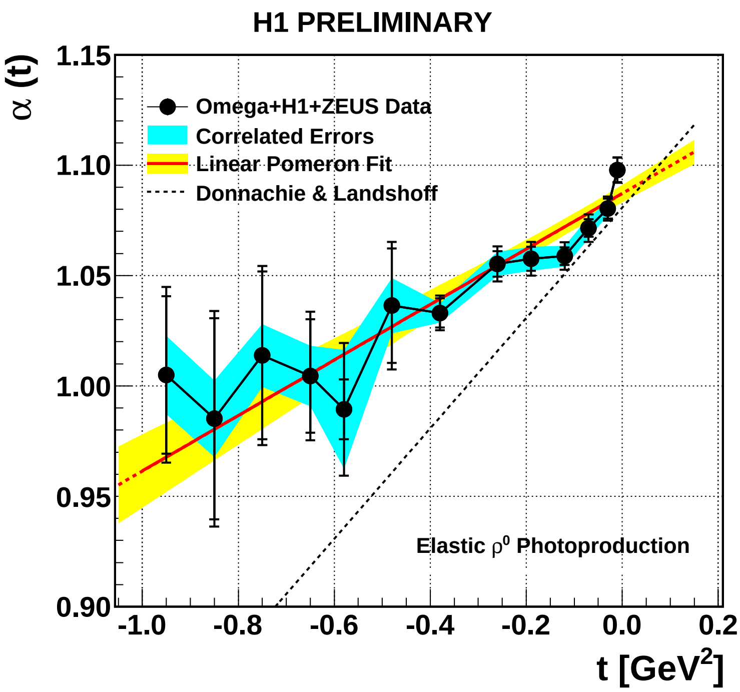

Figure 3: The same as Fig. 2, but with a linear fit of the form $\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P},0} + \alpha'_{\mathbb{P}} \cdot t$.
The result of the fit, which has a $\chi^2/d.f. = 14.7/11$, is
$\alpha_{\mathbb{P},0} = 1.0871 \pm 0.0026(stat.) \pm 0.0030(syst.)$ and $\alpha'_{\mathbb{P}} = 0.126 \pm 0.013(stat.) \pm 0.012(syst.)$ GeV^{-2}.