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Separation of Minimum and Higher Twist in Photoproduction

The OMEGA Photon Collaboration

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Abstract

Photo- and hadroproduction data in the beam energy range 65-175 GeV have been studied with a view to isolating higher-twist processes in photoproduction from other point-like and hadron-like contributions. With selection of charged tracks having $p_T > 2$ GeV/c and $0.28 < x_F < 0.84$ indications of a higher twist contribution have been found at a level that is consistent with QCD expectations.

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1. Introduction

Large-p_T processes in photon interactions are a well-established probe of QCD [1] and provide information on the point-like interactions of the real photon. Data on inclusive $\pi^\pm$ [2,3] and π^0 [4] production at large p_T have been shown to be in good accord with theoretical expectations. These results, which confirm the essential correctness of the dominant minimum twist terms in QCD, lead naturally to the question of whether the much smaller higher-twist processes can be detected in photon interactions. Higher-twist processes in QCD have been the subject of much theoretical discussion [5,6]. Evidence for the observation of higher-twist effects has been found in $\bar{\nu}N \rightarrow \mu^+\pi^-X$ [7], Drell-Yan processes [8],inclusive ρ production in high-p_T πN interactions [9], and in e^+e^- data[10].

The data reported in this paper were the same as were used for a previous study of single high-p_T particles in the WA69 experiment at the CERN SPS[2] and more details are reported there. The total number of photon-induced events was $\approx 2 \cdot 10^7$ over the momentum range $65 < E_\gamma < 175$ GeV/c. A total of $\approx 2 \cdot 10^7$ hadron-induced events ($\pi^\pm$ and $K^\pm$) was also taken at 80 and 140GeV/c. The data were taken with a liquid hydrogen target and an open trigger was used to give a largely unbiased sample of events.

In the present paper, photon interactions are studied in which higher-twist processes are of the type $\gamma q \rightarrow Mq$, where M is a prompt $\pi^\pm$ or $K^\pm$ meson (Fig. 1a). For $p_T > 2.0$ GeV/c the various contributions to the cross section are: the hadron-like part of the photon (described by vector dominance) which still makes a substantial contribution at such p_T values; the QCD minimum twist terms (in lowest order the QCD Compton process $\gamma q \rightarrow gq$ and the QCD Bethe-Heitler process $\gamma g \rightarrow q\bar{q}$ (Figs. 1b,c)) which are of similar magnitude; the direct higher-twist contribution where the prompt meson M is a $\pi^\pm$ or $K^\pm$; and the indirect higher-twist contribution ($M = \rho, \omega, K^o, K^*, \phi, \ldots$) where the final state pion or kaon comes from decay of a directly produced particle or resonance. The distribution of pions and kaons from the indirect contribution is very similar to that from the minimum-twist processes (apart from the normalisation) and is not considered further. The higher-twist contribution to inclusive π/K photoproduction has therefore to be isolated from a large background of hadron-like and minimum twist processes.

The minimum-twist and higher-twist contributions have been calculated with the Monte Carlo program LUCIFER[11]. Topological properties of these events are analysed in section 2. The hadron-like part of the photon was estimated using hadron beam data (denoted as $h^\pm p$ interactions in the following) which consist of $\pi^\pm p$ and $K^\pm p$ interactions mixed in order to reproduce the strange quark content in the photon [2]. These contain diffractive dissociation processes even at high p_T and are discussed in section 3.

As before [2] it is assumed that the three different contributions add incoherently in the cross section, so that the photon data can be fitted with a linear superposition of the three with coefficients to be determined. Results from the fits are presented in section 4.

To determine the experimental acceptances and resolutions a simulation program [12] was used to trace full events through the detector, generating digitisings for the charged particles, which were processed with the track reconstruction program[13]. Quality cuts on tracks have been used as described in [2]. The acceptances are generally high (> 80%) and flat. They do not depend on p_T. Only at high x_F does the acceptance drop, due to the necessity of rejecting e^+e^- pairs in the trigger. Since the high-x_F region is important here, these acceptances have been studied in some detail. The overall acceptance is shown on Fig. 2 for the minimum twist QCD events from the simulation. In the high x_F-region the measurement error in $1/p$ may displace both x_F and p_T to a significant extent. The cuts used here, as in [2], were designed to eliminate badly measured tracks and are believed to lead to a negligible contamination of the data at all x_F. For $x_F < 0.84$, which is the upper bound of the x_F range used for the fits in section 4, the errors of x_F were found to be smaller than the bin size.

2. Monte Carlo studies of the QCD processes

To obtain an understanding of the topological nature of different types of QCD processes, extensive Monte Carlo studies have been carried out. In these studies the LUCIFER Monte Carlo program [11] and an adaptation of the LUND string fragmentation model JETSET 6.3 [14] for the lowest order minimum-twist processes and for higher-twist processes, were used. A Monte Carlo sample of about ten times the photon data statistics ($\approx 1pb^{-1}$) was generated.

As discussed above, the characteristic signature of higher-twist processes is the occurrence of the prompt meson instead of a second forward cluster. The simulation shows that the prompt $\pi^\pm$ or $K^\pm$ corresponds to the highest p_T particle in over 98% of the events and that the x_F distribution peaks at $x_F \approx 0.8$. In order to have reliable theoretical calculations and to exclude a sufficient fraction of the hadron-like photon interactions it is necessary to restrict candidate higher-twist events to those with a charged particle with $p_T > 2.0$ GeV/c.

Attempts have been made to enrich the content of higher-twist processes by the kinematical isolation of the prompt mesons from other particles in the event. Among others, an isolation measure d_i defined for each track i by

$$d_i = \min_{j \neq i} \sqrt{\frac{(\triangle\phi_{ij})^2 + k \cdot (\triangle Y_{ij})^2}{1+k}} \tag{1}$$

has been studied ($\triangle Y_{ij}$ is the rapidity difference between tracks i and j divided by the maximum kinematically allowed rapidity difference, and $\triangle\phi_{ij}$ is the difference in the azimuthal angle in the plane transverse to the beam divided by π; this therefore selects the particle "next" to the prompt meson candidate. A similar quantity has been used before in isolating inelastic QED Compton events in γp reactions [15]). The value of $k = 2.0$ was found empirically to maximise the selectivity. With the restriction to $p_T > 2.0$ GeV/c, the two-dimensional distributions of x_F and d for both minimum twist and higher twist are shown on Figs. 3(a) and (b), corrected for experimental acceptance effects and using charged particles only. Two projections of the invariant x_F distributions, one with no d cut and the other requiring $d > 0.2$ are given on Figs. 3(c) and (d). Quantifying the power of this isolation measure in terms of σ_{HT}/σ_{MT} it is found that although d has significant enhancement power at lower x_F the enhancement is only of order 20% in the region $x_F > 0.6$ where the higher twist signal is significant compared to the minimum twist. It is thus not possible to improve the selectivity usefully with the isolation variable d and no isolation variable has been used in the remainder of this analysis.

The systematic variations of predicted minimum and higher-twist cross sections due to uncertainties in Λ_{QCD}, the definition of the momentum transfer scale Q^2, the effects of higher order corrections, different sets of structure functions, and the uncertainties in fragmentation schemes have been considered. It was found that although the magnitudes of predicted cross sections could change by a factor of up to 2, the shapes of predicted distributions are subject to minor changes only. As discussed below, systematic effects on fitted cross sections were dominated by the uncertainties in the description of the hadron-like photon. Hence it is sufficient to work with the lowest order calculation and standard LUCIFER parameters (Λ_{QCD} = 300MeV, the structure function set 1 by Eichten et al [16] for the nucleon, and $Q^2 = 2\hat{s}\hat{t}\hat{u}/(\hat{s}^2 + \hat{t}^2 + \hat{u}^2)$).

The absolute predictions of the cross-sections from the simulation are given in columns 2 and 3 of table 1. The relative normalisation of the higher twist with respect to the minimum twist contribution is uncertain within a factor 2 to 4 and is still the subject of theoretical discussion [17]. However the shapes of higher twist distributions are not affected by this.

3. The hadron-like photon component and diffractive dissociation

The backgrounds to the point-like photon contributions are globally described as the hadron-like photon component. This latter component dominates the γp cross section at low p_T (and hence the total cross section). For the p_T-range studied here it cannot be calculated reliably in the framework of QCD, and the hypothesis was made that it can be modelled by $\pi^{\pm}p$ and $K^{\pm}p$ interactions. Thus the hadron-like photon contribution has been represented by an incoherent mixture of two thirds $\pi^{\pm}p$ and one third $K^{\pm}p$ data. The higher-twist contribution to the inclusive $\pi^{\pm}$ cross section in photoproduction is most significant at comparatively large values of x_F. This is the region in which the hadronic data on inclusive $\pi^{\pm}$ and $K^{\pm}$ production contain a significant, even dominant, contribution from diffractive events where the target dissociates.

Fig. 4 shows the measured x_F distribution for single charged particles at $p_T > 2.0$ GeV/c from $h^{\pm}p$ interactions. The contributions to these data from processes with charge difference between the beam and the secondary charged particle, $\triangle Q = 0$ and $|\triangle Q| = 2$, are shown separately. The $\triangle Q = 0$ contribution does not vanish for $x_F \rightarrow 1.0$, giving rise to an excess of charged particles in the high x_F-region in $\pi^{\pm}p$ and $K^{\pm}p$ processes relative to γp processes; this has been observed earlier [2]. This effect is visible in the full p_T range covered by the experiment and is presumably due to diffractive dissociation, despite the fact that diffractive dissociation is conventionally thought of as being a low-p_T phenomenon. Support for the hypothesis that diffractive dissociation persists out to relatively large p_T is given by the successful description of the $\triangle Q = 0$ data at high x_F and $p_T > 1.5$ GeV/c in $\pi^{\pm}p$ with a model which describes well pp diffractive dissociation over a wide range of p_T [18].

Since $\gamma p \rightarrow h^{\pm}X$ is a $|\triangle Q| = 1$ process, the best choice for the representation of the hadron-like photon processes could be the $|\triangle Q| = 1$ cross section from the $h^{\pm}p \rightarrow \pi^0 X$ process. However, the $h^{\pm}p \rightarrow \pi^0 X$ data measured in this experiment are more restricted in p_T and have different detector acceptances. In Fig. 5 the hadroproduction x_F distributions of the $h^{\pm}p \rightarrow h^{\mp}X$ ($|\triangle Q| = 2$) data and $h^{\pm}p \rightarrow \pi^0 X$ ($|\triangle Q| = 1$) data from this experiment [19] are compared for the three p_T ranges 1.2-1.6, 1.6-2.0 and 2.0-2.4 GeV/c. The normalisation of the π^0 data is scaled in order to agree with the $|\triangle Q| = 2$ charged-particle data. Fig. 5 demonstrates that the x_F shapes agree well over a wide range of p_T. Over the relevant x_F range the $\pi^{\pm}p \rightarrow \pi^0 X$ data from [20] also agree satisfactorily.

Although the $h^+p \rightarrow h^-X$ and $h^-p \rightarrow h^+X$ data agree at large x_F, at lower x_F the latter contains a significant contribution due to proton contamination even at $p_T > 2.0$ GeV/c. Since these effects will be different again for the photon data, this constrains the comparison to a region where effects due to proton contamination are small. Thus only for $x_F > 0.28$ is the hadron-like part of the photon sufficiently reliably determined within the model.

It follows that the $|\triangle Q| = 2$ data give the best description available for the x_F distribution of the hadron-like photon. This procedure also minimises acceptance biases (because all the data analysed are from the same detectors) and reduces statistical errors. To normalise this estimate of the hadron-like component of the photon, the cross section for the $|\triangle Q| = 2$ process was scaled by the fraction of $|\triangle Q| = 2$ processes in the total charged particle production cross section in $h^{\pm}p$ interactions and by the VMD factor of 215 derived from lower x_F and p_T data in this experiment [2]. The estimated cross sections for the hadron-like photon contribution are shown in column 1 of table 1.

4. Fitted Cross Sections

To estimate the amounts of the various contributions to the data, fits to the photon-induced data were made assuming a linear and incoherent superposition of the contributions from the hadron-like photon, minimum twist and higher twist. With the normalisations of the hadron-like photon and minimum and higher-twist processes given in table 1 and discussed in sections 2 and 3, the absolute magnitudes of fitted parameters a_H, a_{MT} and a_{HT}, being the ratios of the fitted to predicted cross sections, should be close to 1.

Photon-induced data were selected within two incident momentum bins, from 70 to 90 GeV/c and 110 to 170 GeV/c. These ranges are matched with hadron beam data at 80 GeV/c and 140 GeV/c respectively. It was important that fits only included regions where trigger and other acceptances were reasonably high and sufficiently well determined and where the shapes of the input distributions were reliably known. Hence the data were selected for $p_t > 2.0$ GeV/c and $0.28 > x_F > 0.84$.

In the x_F range considered the hadron-like component and the minimum-twist are strongly correlated and not well determined individually. The results of the fits for $p_T > 2.0$ and 2.3 GeV/c are summarised in table 2 (fixed parameters are those shown without errors). In Figs. 6a and 6b the fits for $a_H = 1.0$ and $p_T > 2.0$ GeV/c are shown for both beam energies. The full curve represents the overall fit function and the individual contributions from the hadron-like photon (— — — — —), minimum-twist (— · — · —) and higher-twist (· · · · ·) as determined by the fit are also indicated. Corresponding fits shown in Figs. 6c and 6d demonstrate how the quality of the fits is degraded if the higher-twist contribution is set to zero. These results show that including the higher-twist contribution, which is insensitive to the relative normalisation of the two major components, leads to a better description of the data at the highest x_F.

5. Summary and Conclusions

The contributions of point-like and hadron-like interactions in the photoproduction of events with high p_T tracks have been studied using the x_F distributions of single charged particles at $p_T > 2.0$ GeV/c. This analysis is sensitive to the existence of higher-twist processes where the prompt meson is a $\pi^{\pm}$ or a $K^{\pm}$. The photoproduction cross section in this kinematical region has been assumed to be described by a linear and incoherent superposition of three components: hadron-like photon, minimum twist and higher twist. The hadron-like contribution to photoproduction has been estimated from hadron-induced data taking into account effects due to the charge difference between the initial and final state particles. The shapes of the minimum-twist and higher-twist contributions have been modelled with QCD and their magnitudes fitted. The magnitude of the small higher-twist cross section has been found to be insensitive to the relative normalisation between the two dominant contributions, to the method of modelling the hadron-like photon and to the QCD parameters used in the Monte Carlo calculations. The data support a contribution from higher-twist processes to the photoproduction of charged particles at high x_F which is consistent with the theoretical predictions of QCD [17].

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Table Captions

Table 1 Cross sections (nb) predicted for the hadron-like photon and mimimum and higher twist contributions, and measured cross section for γp interactions. Errors on measured cross sections are dominated by a 15% systematic uncertainty; the minimum-twist term is estimated to be correct to within 20% [1]; and there is a factor of 2 to 4 uncertainty on the higher-twist term.

Table 2 Ratios of fitted to predicted cross sections for the hadron-like photon and minimum and higher twist processes.

Figure Captions

Fig. 1 The (a) higher-twist, (b) QCD Compton and (c) QCD Bethe-Heitler processes.

Fig. 2 The x_F-acceptance for the minimum-twist events from LUCIFER for $E_\gamma = 140$ GeV and $p_T > 2.0$ GeV/c showing the full acceptance effects, including the trigger, track finding probabilities and the quality cuts from [2].

Fig. 3 The x_F-d distributions of minimum and higher twist events generated by LUCIFER for $E_\gamma = 140$ GeV and $p_T > 2.0$ GeV/c; the multiplicative factor $x_R = \sqrt{x_F^2 + x_T^2}$ is used to provide the invariant form of the cross section.

Fig. 4 Single charged-particle cross sections for the hadron beam data, separated according to the charge difference $|\triangle Q|$ of beam and secondary particles for $E_{beam} = 140$ GeV and $p_T > 2.0$ GeV/c. (The curve is a smooth parameterisation which has been used to describe the data in the fits in Section 4.)

Fig. 5 Comparison of data for $|\triangle Q| = 2$, $h^\pm p \to h^\mp X$ (•); and $|\triangle Q| = 1$, $h^\pm p \to \pi^0 X$ (○), for $E_{beam} = 140$ GeV. The data are shown for the p_T-ranges (a) 1.2-1.6, (b) 1.6-2.0 and (c) 2.0-2.4 GeV/c.

Fig. 6 Fitted x_F distributions of charged particles in γp interactions for (a) $70 < E_\gamma < 90$ GeV and (b) $110 < E_\gamma < 170$ GeV in the range $p_T > 2.0$ GeV/c and $0.2 < x_F < 0.84$. The full curve shows the overall fit. Also the individual components calculated by the fit are shown: hadron-like photon (— — — — — —), minimum twist (— · — · —) and higher twist (·····). The corresponding results with a higher-twist component fixed to zero are shown in (c) and and (d) for the low and high beam-energies respectively.

Table 1a. ($110 < E_\gamma < 170$ GeV and $0.28 < x_F < 0.84$)

	hadron-like photon	minimum twist	higher twist	photon data
$p_t > 2.0$GeV/c	20.9	23.8	3.7	68
$p_t > 2.3$GeV/c	8.6	10.6	1.8	28

Table 1b. ($70 < E_\gamma < 90$ GeV and $0.28 < x_F < 0.84$)

	hadron-like photon	minimum twist	higher twist	photon data
$p_t > 2.0$GeV/c	11.6	17.5	3.0	45
$p_t > 2.3$GeV/c	3.6	6.6	1.3	17

Table 1

Cross sections (nb) predicted for the hadron-like photon and mimimum and higher twist contributions, and measured cross section for γp interactions. Errors on measured cross sections are dominated by a 15% systematic uncertainty; the minimum-twist term is estimated to be correct to within 20% [1]; and there is a factor of 2 to 4 uncertainty on the higher-twist term.

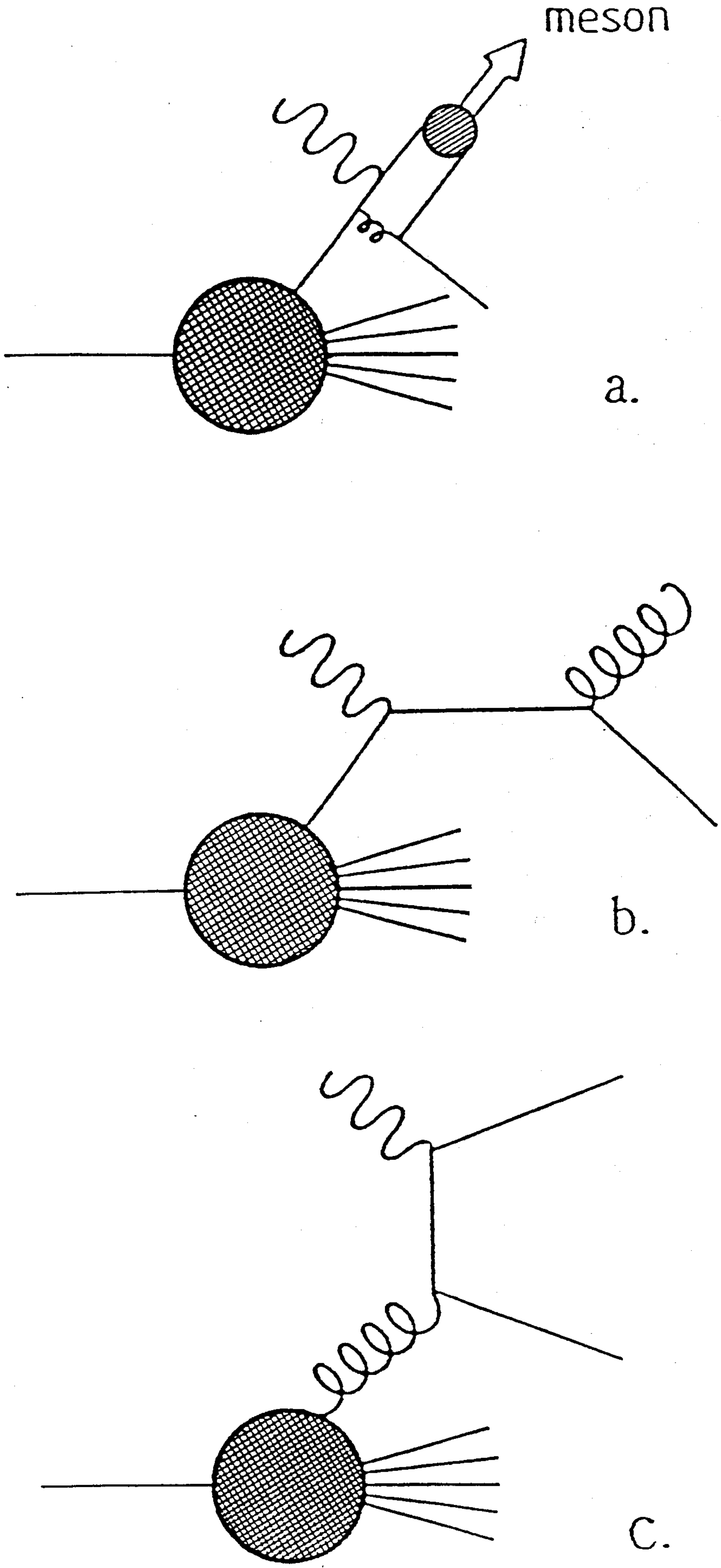
Table 2a. ($110 < E_\gamma < 170$ GeV and $0.28 < x_F < 0.84$)

	a_H	a_{MT}	a_{HT}	χ^2/NDF
$p_t > 2.0$GeV/c	1.0	1.47 ± 0.11	3.15 ± 0.70	0.58
	1.42 ± 0.10	1.0	3.72 ± 0.60	0.66
	1.0	1.88 ± 0.06	0.0	2.10
$p_t > 2.3$GeV/c	1.0	1.37 ± 0.18	2.37 ± 1.08	1.13
	1.56 ± 0.22	1.0	2.08 ± 1.03	0.95
	1.0	1.71 ± 0.09	0.0	1.41

Table 2b. ($70 < E_\gamma < 90$ GeV and $0.28 < x_F < 0.84$)

	a_H	a_{MT}	a_{HT}	χ^2/NDF
$p_t > 2.0$GeV/c	1.0	1.42 ± 0.14	2.52 ± 0.78	1.74
	1.48 ± 0.16	1.0	3.24 ± 0.62	1.81
	1.0	1.79 ± 0.07	0.0	2.40
$p_t > 2.3$GeV/c	1.0	1.65 ± 0.22	2.44 ± 1.19	0.99
	2.08 ± 0.48	1.0	4.35 ± 0.77	1.27
	1.0	2.04 ± 0.12	0.0	1.24

Table 2
Ratios of fitted to predicted cross sections for the hadron-like photon and minimum and higher twist processes.



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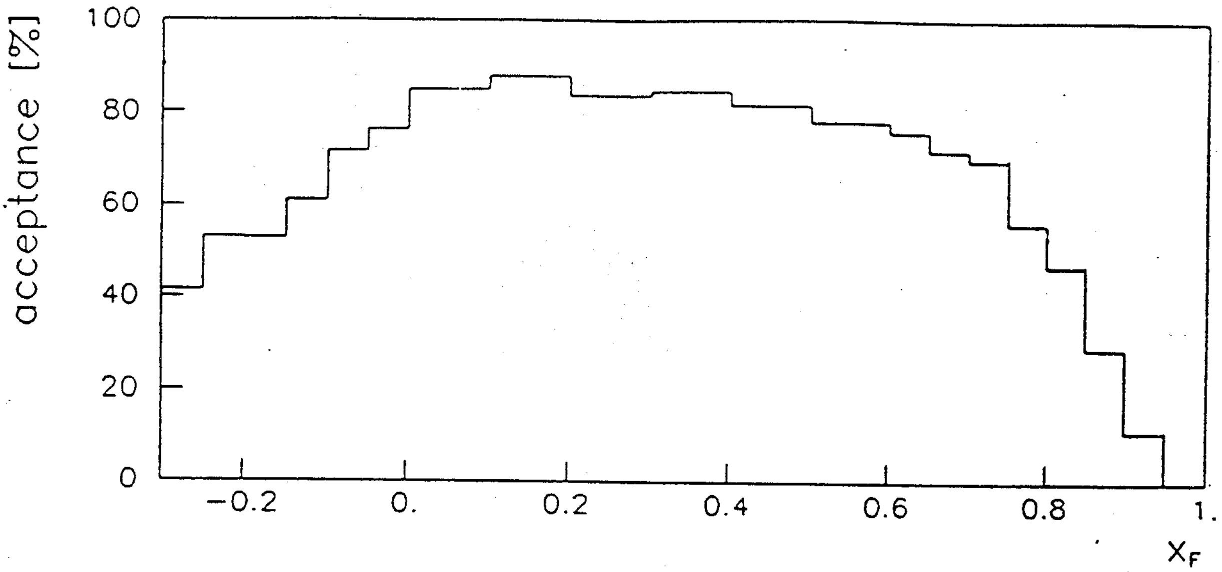

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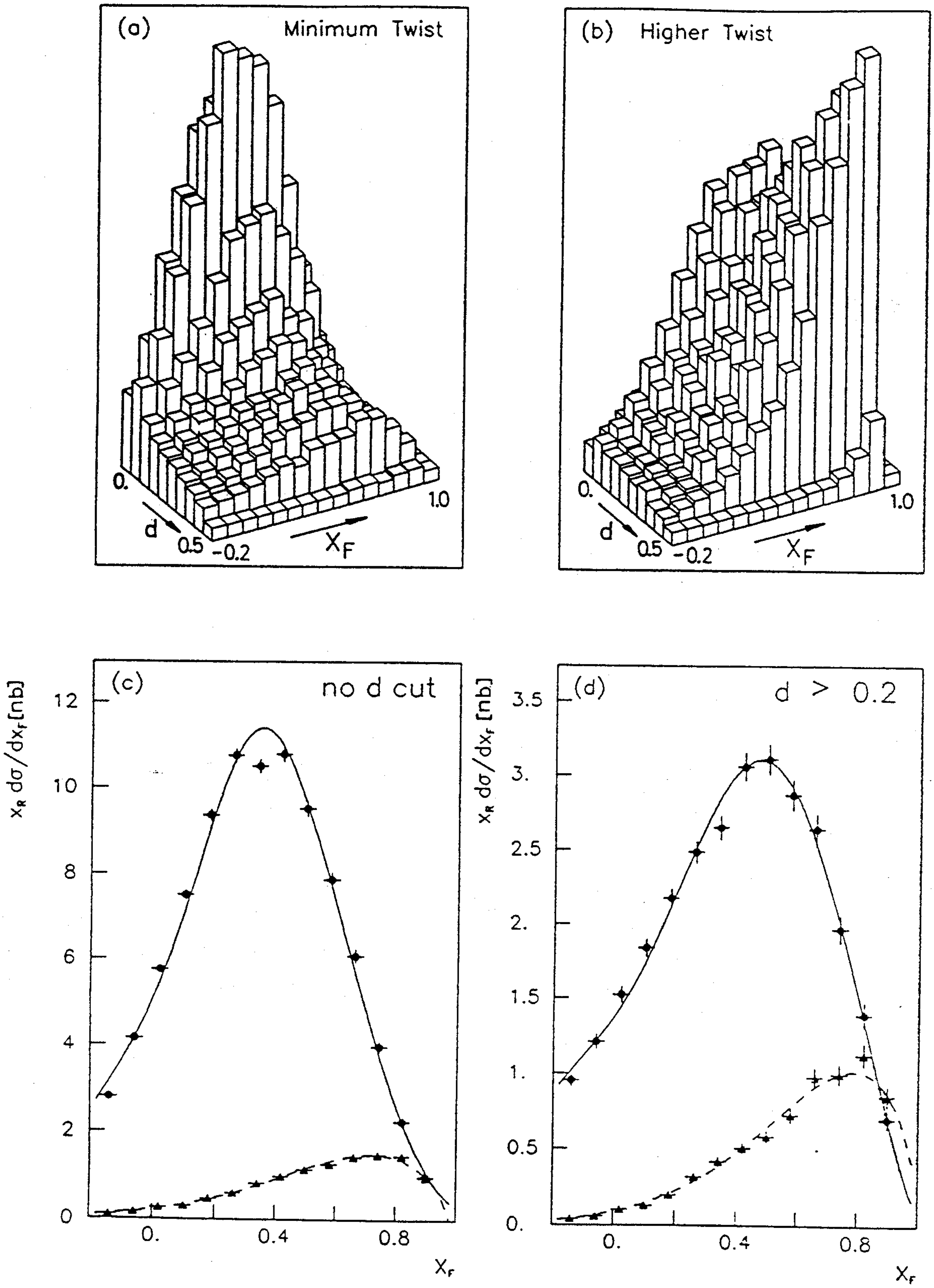

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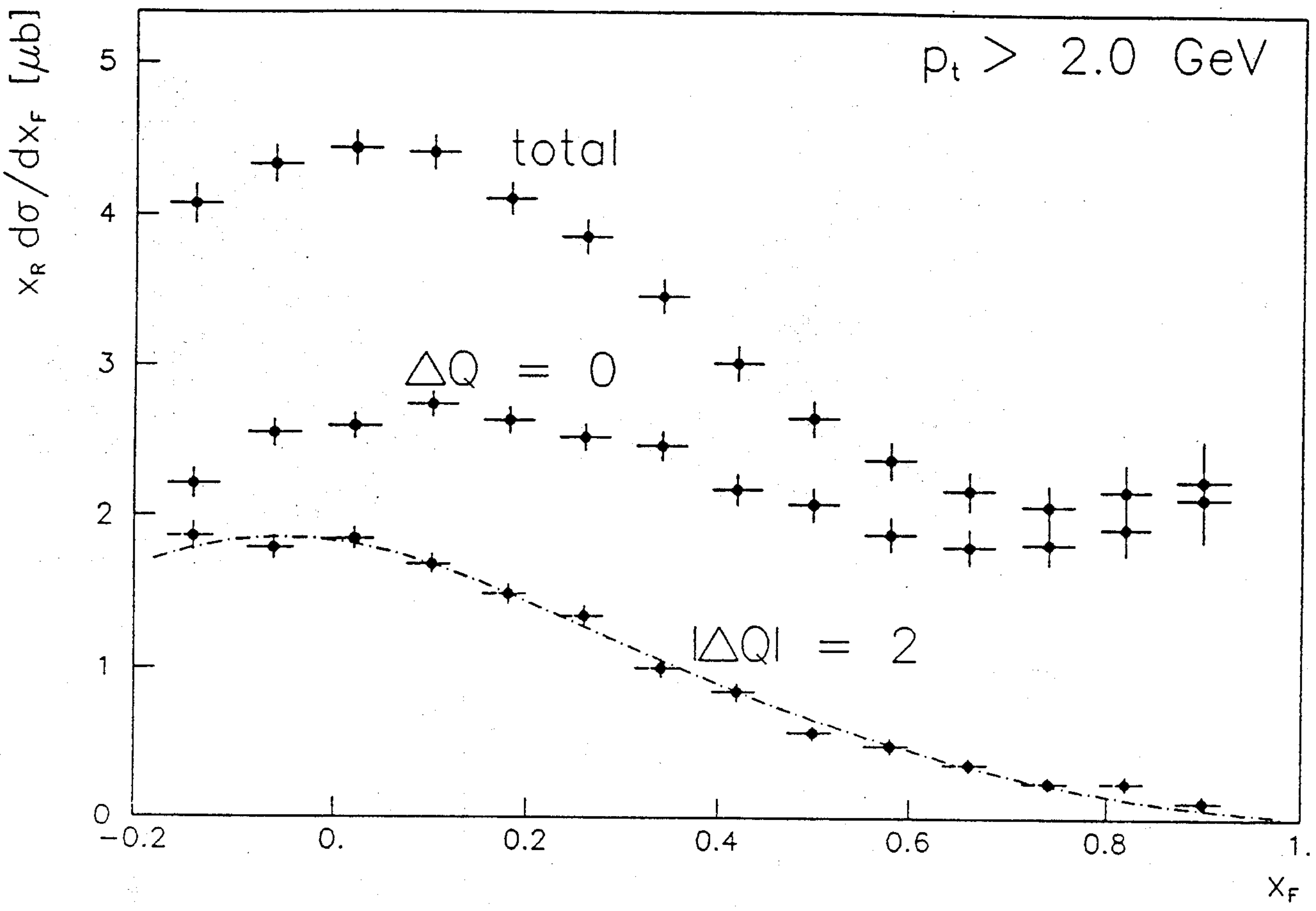

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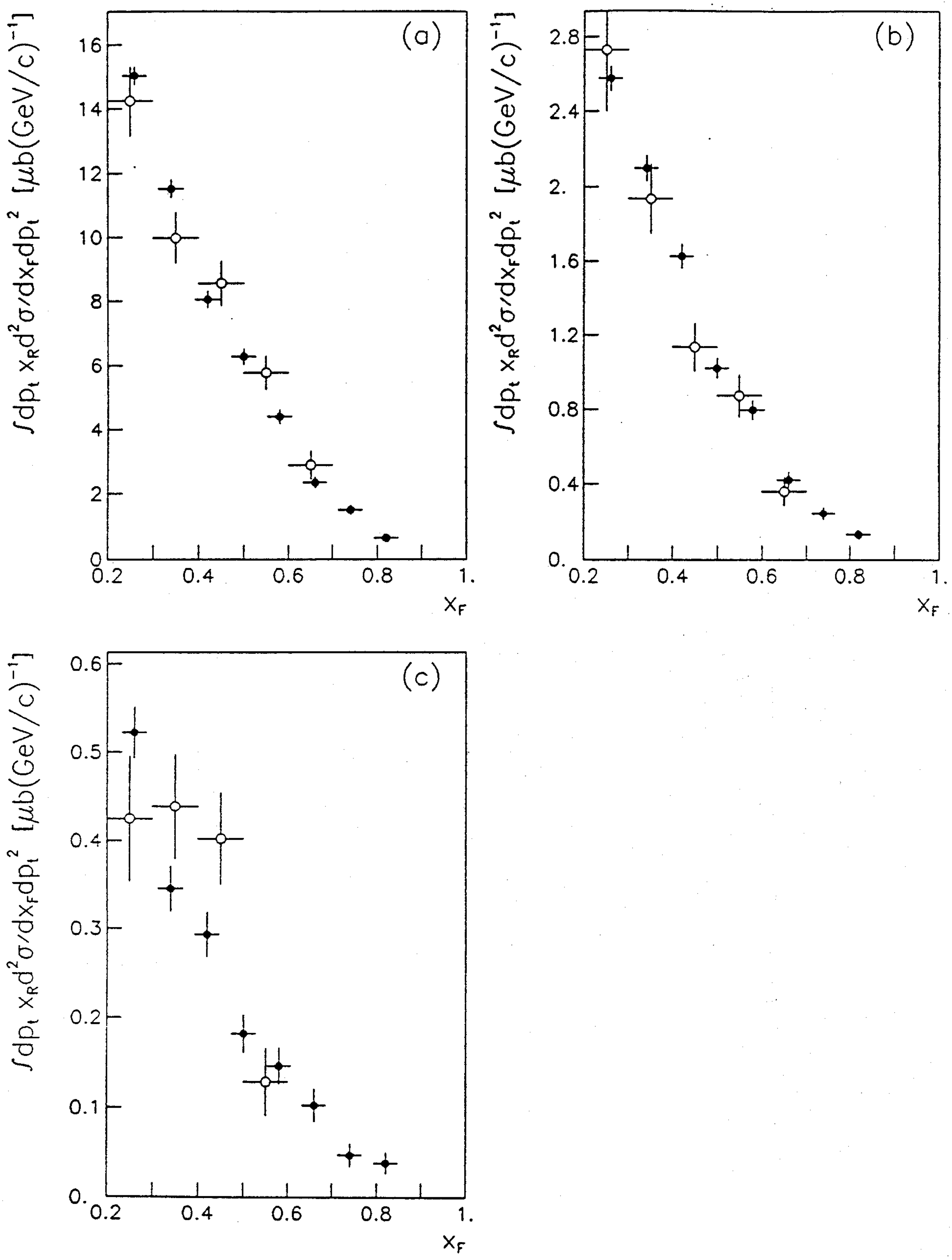

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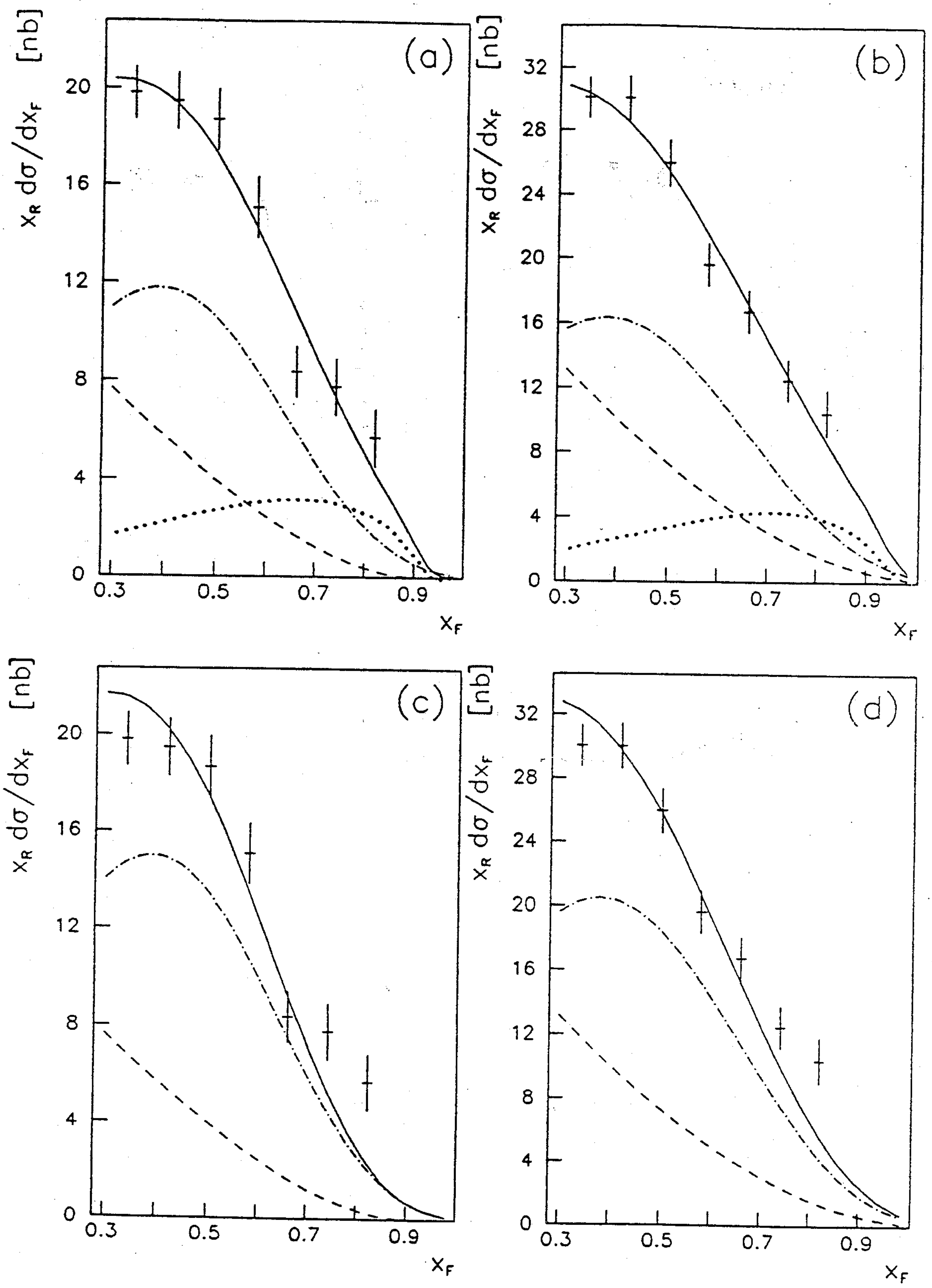

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