

A HIGH-STATISTICS STUDY OF Υ -MESON PRODUCTION IN π^- -W REACTIONS AT 286 GeV/c

NA10 Collaboration

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With a sample of about 2000($\Upsilon + \Upsilon' + \Upsilon''$) events observed in π^- -W interactions at 286 GeV/c, the ratio $(\Upsilon' + \Upsilon'')/\Upsilon = 0.51 \pm 0.07$, the branching ratio times the inclusive total cross section $B\sigma = (386 \pm 17 \pm 85)$ pb per W nucleus, as well as the differential cross sections in x_1 and p_1 have been measured. These results are compared with previous data obtained with the same apparatus at a lower beam momentum (194 GeV/c). Both data sets are compared with a theoretical calculation ("duality model") which also allows one to extract the shape parameter β_g of the gluon distribution in the pion. β_g is found to be $2.3^{+0.4}_{-0.3}(\text{stat})^{+0.0}_{-0.1}(\text{syst})$.

Since its discovery in 1977 [1], hadronic production of the Υ resonances has been studied by a number of experiments using proton beams [2,3]. Extensive quantum chromodynamics (QCD) studies [4-6] have shown that at "low" energies ($\sqrt{s} \approx 15-30$ GeV) Υ production in proton interactions proceeds mainly via gluon-gluon fusion. A better understanding of the production mechanism can be obtained by studying reactions where valence antiquarks are present in the beam particle, so that

quark-antiquark annihilation becomes the dominant process producing particles containing heavy quarks. In this case the theoretical predictions suffer less from structure function uncertainties, since the valence-quark density distributions are better known than the gluon density distributions. Data with other types of beam particles ($\pi^\pm$, K) exist but are scarce [7]. In this paper we present π^- -W data taken at 286 GeV/c and compare them with our previous results at 194 GeV/c [8] as well as with a theoretical prediction. Preliminary results of this analysis have already been presented [9]. Our Υ data at two energies increase the previously available statistics on Υ production by pions by one order of magnitude.

The measurements were performed at the CERN

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Super Proton Synchrotron (SPS) with the NA10 spectrometer, which has been described in detail elsewhere [10]. Dimuons were produced with a high-intensity pion beam (up to $10^9 \pi^-$ per burst) impinging on a tungsten target. A targeting efficiency of 100% was assured by choosing a target diameter of 18 mm, whilst the beam spot size was only 5 mm (FWHM). A 4.8 m long hadron absorber acted as beam-dump and muon filter. Dimuon events were triggered by two pairs of scintillator hodoscopes placed upstream and downstream of a toroidal spectrometer magnet. The muon trajectories were measured with two sets of 12 multewire proportional chambers (MWPCs), one upstream and one downstream of that magnet. Already at the trigger level a rough mass determination was possible, enabling the selection of high-mass events. Special care was given to the measurement of the pion intensity ($\pm 4\%$) and to the overall detection efficiency.

The data presented here come from two running-periods which accumulated comparable statistics (53 000 events with $M > 4 \text{ GeV}/c^2$ recorded in 1983; 42 000 events in 1985). Whereas only a 12 cm long target was used in 1983, the 1985 period was shared between a 5.6 cm target (40% of the events) and a 12 cm target (60%). Some minor spectrometer differences decreased the acceptance slightly in 1985. We analysed the two data sets separately and combined the results after acceptance corrections had been applied.

A Monte Carlo program was used to calculate the acceptance of our spectrometer. For the Υ event generation, x_T and p_T distributions measured in J/ψ production were used in first approximation, and modified to be consistent with our data at both energies. An isotropic angular distribution for the Υ decay into two muons was assumed. The influence of the beam momentum bite and of the nuclear Fermi motion was taken into account in the acceptance calculation. The acceptance for Υ events at $286 \text{ GeV}/c$, as calculated by this simulation program, rises from 12.6% at the Υ to 13.6% at the Υ'' .

Fig. 1 shows the dimuon mass distribution for (a) the 1983 and (b) the 1985 data. In each case the full line represents a fit of the form $f(M) \sim \exp(-aM - bM^2 - cM^3 - dM^4)$ to the Drell-Yan continuum, with a χ^2/NDF of (a) 25.2/26 and (b) 40.8/38. The excess of events in the Υ -mass region

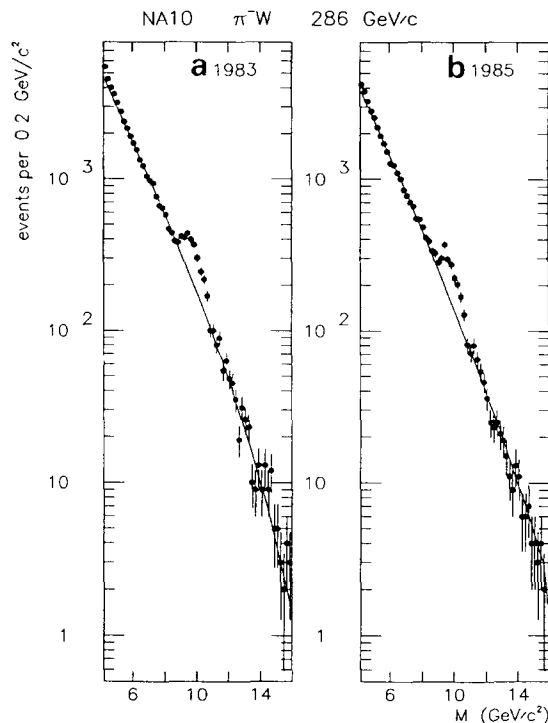


Fig. 1 The $\mu^+\mu^-$ mass spectrum with the Υ peak around $9.5 \text{ (GeV}/c^2)$, for the runs in (a) 1983 and (b) 1985. The Drell-Yan continuum below and above the Υ region was fitted to an exponential $\sim \exp(-aM - bM^2 - cM^3 - dM^4)$ (solid line).

[$8.4, 11.0 \text{ GeV}/c^2$] (which was excluded from the fit) corresponds to $1140 \pm 65 \pm 80 (\Upsilon + \Upsilon' + \Upsilon'')$ events in 1983 and $910 \pm 60 \pm 60$ events in 1985. These errors are statistical and systematic, respectively, the systematic error having been estimated from a series of different continuum fits. The Υ -family mass spectrum is obtained by subtracting the fitted continuum distribution, and is shown in fig. 2.

In the Monte Carlo simulation we generated the three members of the Υ family with masses according to the published values [11]. By fitting the observed Υ peak with these simulated distributions we found a mass shift of only $+40 \text{ MeV}/c^2$ between Monte Carlo events and real data, which means that our experimental mass scale is correct to better than 0.5%. Leaving the ratios $\Upsilon'/\Upsilon/\Upsilon''$ free, a least-squares fit yielded $(\Upsilon' + \Upsilon'')/\Upsilon = 0.47 \pm 0.16$ with a $\chi^2/\text{NDF} = 18.1/9$, in agreement with the result from pN collisions [3]. By fixing the ratio Υ''/Υ' at 0.48 [3], we obtain $(\Upsilon' + \Upsilon'')/\Upsilon = 0.51 \pm 0.07$ ($\chi^2/\text{NDF} = 18.3/10$).

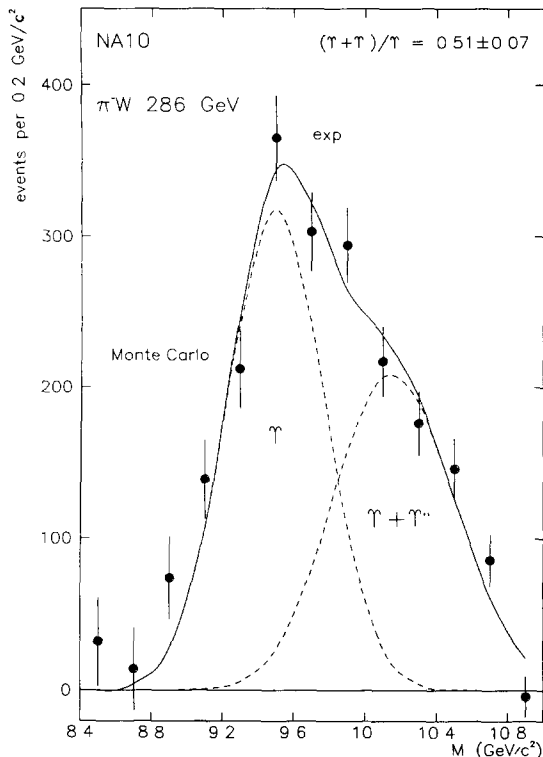


Fig. 2 The Υ peak after subtraction of the continuum as fitted in fig. 1. The 1983 and 1985 data were combined here. The lines represent the mass peaks of the Υ resonances whose ratios were fitted (see text).

Adopting the more accurate $\Upsilon/\Upsilon'/\Upsilon''$ ratios of ref. [3] to compute the acceptance for the Υ family, we obtain a branching ratio times the inclusive total cross section $B\sigma$ of $(393 \pm 22 \pm 86)$ pb per W nucleus for 1983, and $(377 \pm 26 \pm 81)$ pb per W nucleus for 1985, which on the basis of 2050 Υ events yields a final average of $(386 \pm 17 \pm 85)$ pb per W nucleus. An earlier measurement with π^- of 280 GeV/c by NA3, based on 66 events [7], was done on a Pt target. Assuming a linear A dependence their transformed cross section of (441 ± 165) pb per W nucleus is consistent with our finding. This is less true of a subsequent result [12] at the same energy: $(622 \pm 75 \pm 66)$ pb per W nucleus based on 317 events.

In order to extract the branching ratio times the differential cross sections $B d\sigma/dx_F$ and $B d\sigma/dp_T$, we used the same method as for the total cross section, but applying the subtraction procedure in specific x_F and p_T bins (8 and 12, respectively). Fig. 3a and 3b show the combined result from the 1983 and 1985 runs.

In fig. 3b the p_T distribution of the Drell-Yan continuum in the Υ -mass region is indicated by the dotted line. It was determined from the average of the Drell-Yan p_T distributions [13] for the masses immediately below and above the Υ region. As at 194 GeV/c [8], the distributions of continuum events and of Υ events are quite similar. As can be seen in table 1, this is also true for the mean values of p_T which were calculated from a fit to the observed distribution; for the Υ events at 286 GeV/c we find $\langle p_T \rangle_{\Upsilon} = (1.10 \pm 0.04)$ GeV/c.

Comparing the 194 and 286 GeV/c data (see table 1), the most striking difference is found to be the rise in the total cross section by more than a factor of 2. A rise is expected since these energies are still close to the threshold for Υ production. However, the shapes of the observed differential cross sections (fig. 3 in this letter, fig. 2 in ref. [8]) reveal no significant differences between the two energies. The ratios $(\Upsilon' + \Upsilon'')/\Upsilon$ and the mean values $\langle p_T \rangle_{\Upsilon}$ also coincide (table 1). We take this as an indication that the production mechanism is essentially the same at both energies.

Hadronic quarkonium production can be calculated using the so-called duality hypothesis [14], as done by Glück, Owens and Reya [4, 5] for J/ψ and Υ production. In this model the fundamental cross sections at the parton level are calculated via perturbative QCD; $q\bar{q}$ annihilation and $g\bar{g}$ fusion contribute to the formation of a free $b\bar{b}$ pair in lowest order. The parton cross sections are convoluted with the quark and gluon distributions of the particles involved, and integrated over the squared momentum transfer Q^2 from the $b\bar{b}$ production threshold to that of $B\bar{B}$ ($B \equiv b\bar{q}$) production. After summing over flavours and spins, one has to multiply the theoretical cross section with a "fudge factor" F . This factor is meant to represent the probability of formation of a specific bound state in the mass interval between the thresholds for hidden beauty (Υ) and open beauty (B) meson production. This factor cannot be reliably calculated by theory. Thus, duality calculations have to be normalized to (at least) one measured data point in order to be compared with experimental cross sections.

Independently of the normalization, the shape of duality-predicted differential cross sections can be compared with experimental distributions. In fig.

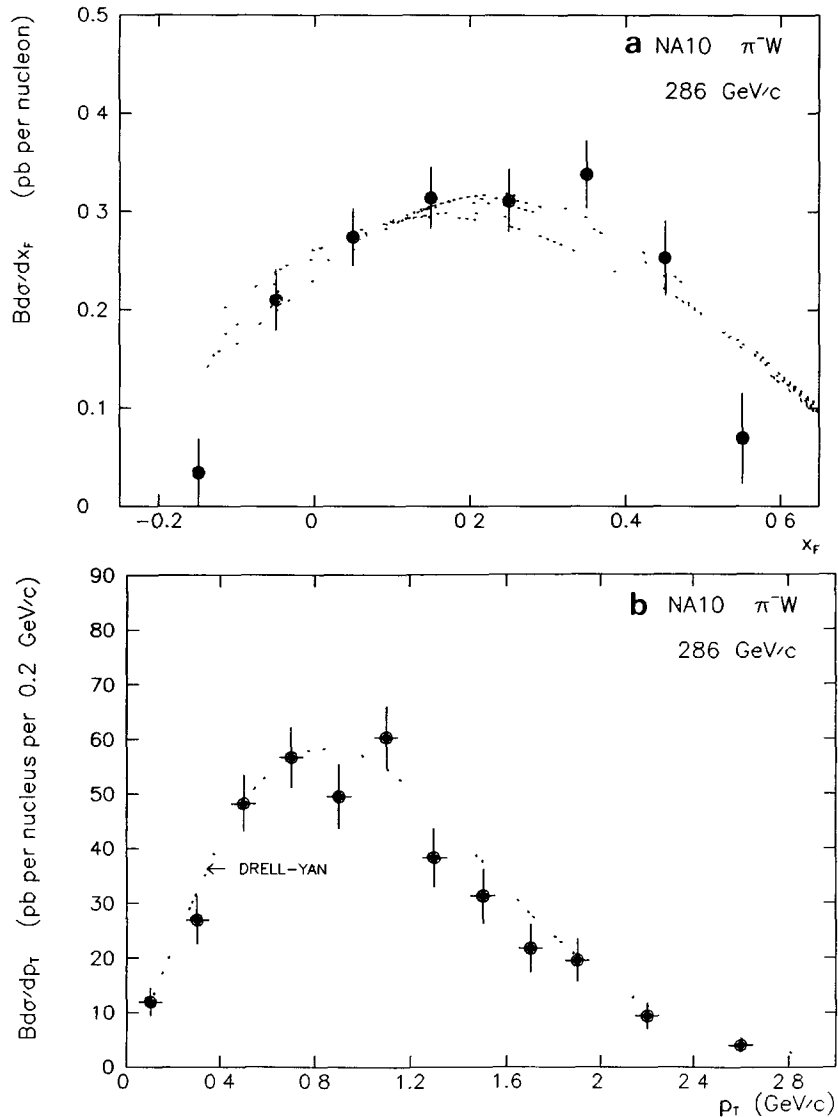


Fig. 3 (a) The Υ differential cross section $B d\sigma/dx_F$. The dotted area corresponds to duality model predictions (normalized to the same total cross section) using different sets of parton distributions (b) The Υ differential cross section $B d\sigma/dp_T$. The dotted line is an estimate of the Drell-Yan p_T distribution in the Υ mass region from an interpolation of our p_T data below and above the Υ region

3a we make this comparison for $B d\sigma/dx_F$. Since the parton distributions represent an external input to the predictions, we performed the calculations with several different sets for the nucleon and pion structure functions [15–21] in order to check for uncertainties due to these inputs. On the one hand, we adopted the two sets of proton and pion structure functions derived by Duke and Owens [18, 19], and on the

other, the pion structure functions extracted from our own continuum data at 194 GeV/c [20] with the corresponding three proton structure functions [15–17] and the pion-gluon distribution from ref. [21]. All predictions lie in the dotted area in fig. 3a, which can thus be taken as an indication of the uncertainty of the predictions which is due to the parton distributions. As at 194 GeV/c, good agreement between this theory and our data is observed.

Table 1
 Υ production in the NA 10 experiment

	194 GeV/c	286 GeV/c
$\sqrt{s}$ [GeV]	19.4	23.1
$N(\Upsilon + \Upsilon' + \Upsilon'')$	$2000 \pm 90 \pm 100$	$2050 \pm 90 \pm 140$
$B\sigma$ [pb per W nucleus]	$176 \pm 7 \pm 31$	$386 \pm 17 \pm 85$
$B d\sigma/dy$ ($y=0$) [pb per W nucleus]	$196 \pm 26 \pm 39$	$362 \pm 46 \pm 108$
$(\Upsilon' + \Upsilon'')/\Upsilon$	$0.52 \pm 0.08^{a)}$	0.51 ± 0.07
$\langle p_T \rangle_1$ [GeV/c]	1.12 ± 0.05	1.10 ± 0.04
$\langle p_T \rangle_{DY}$ [GeV/c]	1.10 ± 0.05	1.21 ± 0.05

^{a)} This error is smaller than that quoted in ref. [8], as it results from a fit with the ratio Υ''/Υ' fixed as in the present analysis.

Fixing the nucleon-quark and nucleon-gluon distributions and the pion-quark distributions, we can (within the framework of the duality model) determine the pion-gluon distribution in a fit to the experimental cross section $d\sigma/dx_F$. Choosing a distribution of the form $xG^\pi(x) \sim (1-x)^{\beta_g}$ with the integral $\int_0^1 G^\pi(x) dx = \langle g_\pi \rangle$ fixed at 0.47 [22], we obtain from a simultaneous fit to our data at 194 GeV/c and at 286 GeV/c, $\beta_g = 2.3 \pm_{-0.3}^{+0.4}$ (stat.) $\pm_{-0.5}^{+0.1}$

(syst.) The fitted cross section is shown in fig. 4. The systematic error takes into account uncertainties from the nucleon-parton and pion-parton distributions and was estimated by repeating the fit with different sets of distributions [15–21]. The uncertainty in the integral of the gluon distribution was taken into account by varying $\langle g_\pi \rangle$ by $\pm 30\%$. This value of β_g is determined at a squared momentum transfer Q^2 which corresponds to the squared mass of the Υ ,

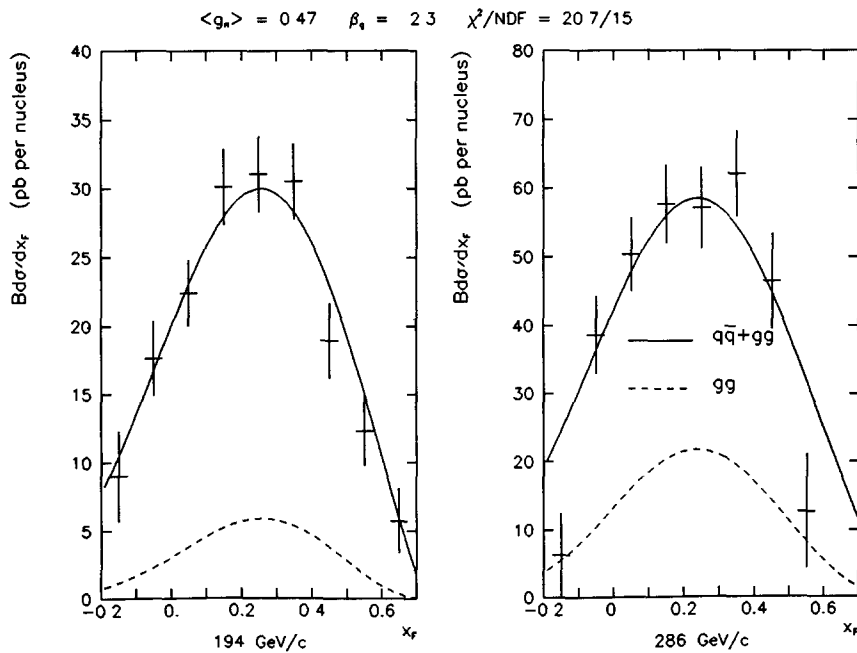


Fig. 4 Determination of the factor β_g of the pion-gluon distribution $G^\pi(x) \sim (1-x)^{\beta_g}$ from a simultaneous fit of duality predictions to the NA10 Υ cross sections at two energies. The other parameters for the nucleon [15] and the pion [20] parton distributions as well as $\langle g_\pi \rangle$ were kept fixed. The solid line is the sum of the quark and gluon cross sections, whilst the dashed line gives the contribution from gluon fusion alone.

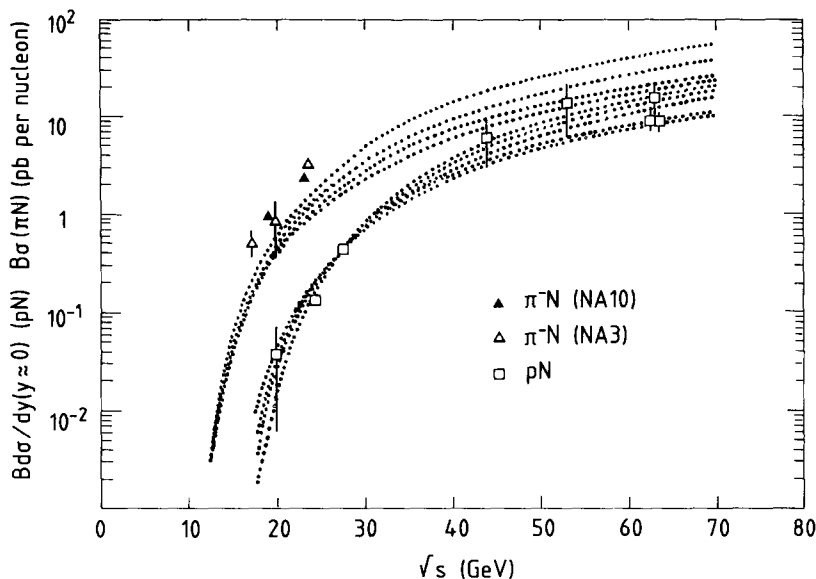


Fig. 5 Energy dependence of hadronic Υ production in p-N and π -N reactions. The proton induced Υ cross sections are given at $y=0$, except those at 19.9 and 24.3 GeV which were obtained at $y=0.2$. Since the y -distributions of the Υ resemble those of the continuum and since the latter distributions are rather flat between $y=0$ and $y=0.2$ (see ref. [3]), the above-mentioned cross sections are not expected to be very different from those at $y=0$. The dotted regions correspond to duality model predictions for both types of reactions with different sets of parton distribution functions.

$M_Y^2 \approx 100 \text{ GeV}^2$. A similar determination [21] of β_g from J/ψ data ($Q^2 \approx M_{J/\psi}^2 \approx 10 \text{ GeV}^2$) yielded $\beta_g = 2.38 \pm 0.06 \pm 0.10$; despite the different value of Q^2 , the two results for β_g are quite consistent.

In fig. 5 we show a compilation of Υ production cross sections in pN [2, 3] and π N (from refs. [7, 8] and this paper) interactions together with duality predictions for the energy dependence of the cross section. For the purpose of this plot a linear A dependence of the cross sections has been assumed in order to compare the different experiments. The uncertainty due to the parton distributions used is indicated in the same way as in fig. 3a, i.e. all predictions lie in the shaded area for pN or π N interactions, respectively. All curves were normalized to the most accurate data point, i.e. to the pN cross section at $\sqrt{s} = 27.4 \text{ GeV}$ [3]. The observed rise in the total cross section above threshold is well explained for both types of reactions. However, if one normalizes to the pN data (as is done here), the π N predictions are three to five times lower than observed. This means that duality does not predict the ratio $\sigma(\pi N \rightarrow \Upsilon)/\sigma(pN \rightarrow \Upsilon)$ correctly. Owing to the small

errors of our data this is statistically significant ($\approx 10\sigma$ to 15σ). One possible explanation is that additional contributions from $q\bar{q}$ processes (which, at those energies where π N data are available, are more important in pion reactions than in the proton case) are not accounted for in the present calculations. Another possibility is that the "fudge factor" F is not the same for proton and pion reactions. This observation is in contradiction with the J/ψ case where the duality model well describes both proton- and pion-induced cross sections with the same F factor [4].

In conclusion, we have measured the branching ratio times the inclusive total cross section $B\sigma = (386 \pm 17 \pm 85) \text{ pb per W nucleus}$ for Υ production by π^- on W at $286 \text{ GeV}/c$. In the range of pion momenta investigated here (194 and $286 \text{ GeV}/c$) the cross section is still rising quickly. The ratio $(\Upsilon' + \Upsilon'')/\Upsilon$ in pion-induced interactions is the same as that in proton interactions. The differential distributions in x_F and p_T at the two energies agree with each other. They also agree well with those of the continuum in the same mass interval. The x_F distri-

bution of the Y can be described by duality-model calculations. The value of the gluon distribution parameter at the mass of the Y ($Q^2 \approx 100 \text{ GeV}^2$), $\beta_g = 2.3^{+0.4}_{-0.3}$ (stat.) $+^{0.1}_{-0.5}$ (syst.), obtained within the framework of such a model from the x_F distribution, turns out to be the same as that obtained at the mass of the J/ψ . Duality calculations also account well for the observed energy dependence of the total cross section; however, they fail to predict absolute cross section values or the ratio between proton- and pion-induced Y production

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