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MEASUREMENT OF THE GLUON STRUCTURE FUNCTION OF THE PION

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ABSTRACT

In experiment WA11, performed at the CERN Super Proton Synchrotron, we have determined the shape of the gluon structure function of the pion to be $(1-x_1)^{1.9\pm0.3}$ from the longitudinal momentum distribution of 38,000 J/ψ produced by collisions of negative pions of momentum 190 GeV/c with beryllium.

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Hadron-hadron interactions at high energy, being the collisions of clouds of partons, are in general very complicated. One of the few examples which can be interpreted as the interaction of two partons only is the Drell-Yan mechanism: a quark and an antiquark annihilate and a muon pair emerges. Measurements on the Drell-Yan process have been used to determine the quark structure functions of hadrons [1-3]. Those for protons agree with the ones derived from deep-inelastic scattering. In addition, Drell-Yan measurements are the only source of quark structure functions for π and K. We have previously discovered that the Drell-Yan predictions are too low by a factor of more than 2 [3]; this effect has also been seen in other experiments [4]. Higher-order quantum chromodynamics (QCD) calculations can account for this factor. Moreover, the theoretical correction to the hadron structure function is a multiplicative factor independent of x, which is consistent with experimental observation for the proton [5].

In this paper we use the production of J/ψ in 190 GeV/c π^-N collisions to measure the gluon structure function of the pion. We assume that a substantial fraction of J/ψ mesons is formed by gluon-gluon fusion, in a manner analogous to quark-antiquark annihilation in the Drell-Yan process. Although direct production of J/ψ from two gluons alone is forbidden by spin and parity conservation, we believe that the evaporation of one or more soft gluons should not appreciably affect the validity of the analysis presented here. As in the Drell-Yan process, higher-order QCD corrections may be important, but we have assumed that, as in the case of quarks, these corrections do not change the shape of the structure functions.

The J/ψ can also be formed by quark-antiquark annihilation. The ratio of the coupling constants for J/ψ quark-antiquark and for J/ψ gluon-gluon has been extracted from data on J/ψ production by proton and antiproton beams obtained by the NA3 Group at CERN [6,7]. Using either naive structure functions [8] or measured structure functions [9] we have calculated that for 190 GeV/c π^- incident on Be the contribution of gluon-gluon fusion is $(50 \pm 10)\%$ [10]. We will therefore assume that gluon-gluon fusion contributes a substantial fraction of the J/ψ produced in 190 GeV/c π^-N interactions. The precise value of this fraction will affect the normalization, but will in fact not alter very much the shape of the structure function obtained in this analysis.

The experiment was performed at the CERN Super Proton Synchrotron (SPS). A high-resolution open-geometry magnetic spectrometer GOLIATH was triggered on muon pairs created by interactions of π^- mesons on Be with the beam momentum being varied between 175 and 200 GeV/c. The coordinates of outgoing charged particles were measured by 13 chambers inside the magnetic field of GOLIATH and by 3 others further downstream. Muons were identified as particles penetrating 4 m of iron placed after all the chambers. This important difference from "beam dump" experiments gives very good momentum resolution and hence good invariant mass resolution for outgoing states produced in one of the targets. The number of J/ψ produced in this experiment, despite the use of an open spectrometer, is sufficient to make the statistical uncertainties smaller than the systematic errors in this analysis. Details of our apparatus have been presented elsewhere [11].

The measured $\mu^+\mu^-$ invariant mass spectrum is presented in fig. 1. The excellent mass resolution $\sigma = 31$ MeV allows a clear identification of 38,000 J/ψ, with background of about 7% in a mass region from 3.0 to 3.18 GeV/c^2. Approximately 60% of this background is due to the Drell-Yan process, whilst the remainder comes from π and K decays [11].

The measured distribution of longitudinal momentum p_L for muon pairs in the mass range of 3.0 to 3.18 GeV/c^2 is presented in fig. 2a plotted as a function of the parameter $x = 2p_L/\sqrt{s}$. The 7% background to this distribution, also shown in fig. 2a, was determined by using data in the mass regions 2.7 to 2.9 GeV/c^2 and 3.3 to 3.5 GeV/c^2 for each x bin.

It is important to note that not all the J/ψ are produced directly. We have previously determined that $(30.5 \pm 5)\%$ of the J/ψ come from $\chi \rightarrow \gamma(J/\psi)$ decays [12]. Our observations of the decay $\psi' \rightarrow (J/\psi)\pi^+\pi^-$ show that about 8% of the J/ψ come from ψ' decays. We have also established that less than 1% of the J/ψ come from the decay $\chi(3554) \rightarrow (J/\psi)\pi^+\pi^-\pi^0$ [13]; the branching fractions of χ decays to other channels including J/ψ are thought to be small [14].

A correction for χ decay has been introduced in the following way. A gluon fusion model [15] was used to generate J/ψ mesons, by a Monte Carlo method, both directly and by radiative decay from directly produced χ. In both cases muons were tracked through the spectrometer and the acceptance of the apparatus was introduced. The ratio of the x-distributions for accepted J/ψ for these two production modes is shown in fig. 2b. This correction was applied by multiplying 30.5% of the raw data in each x bin, after background had been subtracted, by the appropriate ratio.

The following method was used for calculating the experimental acceptance. A Monte Carlo program generated J/ψ according to a gluon-gluon fusion model [15]. Both muons from J/ψ decay were tracked through the apparatus, and the response of each detector was determined taking into account the appropriate efficiencies of the chambers. This information was then mixed with a real event measured in the experiment. The set of mixed events thus obtained was passed through the standard evaluation program. The J/ψ acceptance obtained in this way has taken into account geometrical losses, mistakes by the pattern recognition program, and the resolution and inefficiency of the apparatus. It is presented in fig. 2c as a function of x. The precision of our x measurement presented in fig. 2d is 0.003 for negative x and increases to 0.023 at x = 0.8.

The corrected J/ψ x-distribution is shown in fig. 3. The error bars in fig. 3 include the statistical errors in the measurements, in the Monte Carlo acceptance and in the background subtraction.

We have fitted the x distribution in fig. 3 to the function:

$$\frac{d\sigma}{dx} = \eta_g \frac{d\sigma}{dx_{gg}} + \eta_q \frac{d\sigma}{dx_{qq}} ,$$

where

$$\frac{d\sigma}{dx_{gg}} = \frac{4\pi^2}{M_\psi^2} \frac{g^2_{\psi gg}}{4\pi} \frac{F_\pi(x_1)\cdot G_N(x_2)}{(x_1 + x_2)} .$$

Here $d\sigma/dx_{gg}$ and $d\sigma/dx_{qq}$ are the cross-sections for gluon-gluon fusion and quark-quark annihilation respectively, whilst η_g and η_q are varied between 0 and 1 and give the fractions of J/ψ production for the two processes; $g^2_{\psi gg}/4\pi$ is the J/ψ two-gluon coupling constant; F_π and G_N are the pion and nucleon structure functions.

We have taken gluon structure functions of the form $(1 - x_2)^b$ and $(1 - x_1)^a$ for the nucleon and for the pion respectively; we have varied the power b for the nucleon between 4 and 7, and fitted the power a for the pion. We have fitted also the power a in conjunction with the Q^2-dependent gluon structure function for the nucleon given by the CDHS group at CERN [16]. In addition, we have tested the sensitivity of the fit to different fractions of quark-antiquark contribution to the production of J/ψ.

The smooth curve in fig. 3 is a fit with $\eta_g = 1.0$ (gluon-gluon fusion alone), using for the nucleon the gluon structure function obtained by CDHS [16] at $Q^2 = 9.6\ \mathrm{GeV}^2/c^2$ ($= M_\psi^2$) and for the pion the gluon structure function of the form

$$(1 - x_1)^{1.9} .$$

We get an upper limit to the value of the J/ψ two-gluon coupling constant of

$$g^2_{\psi gg}/4\pi = 2.7 \times 10^{-5}$$

by normalizing $G_N(x_2)$ to 54% [16] and $F_\pi(x_1)$ to 50%, and by taking the total cross-section for J/ψ production to be 116 nb [12]. This limit is obtained for $\eta_g = 1.0$, for which we get the minimum χ^2. We are unable to determine the fraction of J/ψ production by gluon-gluon fusion and therefore the value and error of the coupling constant.

The dashed curve in fig. 3 is for production entirely by quark-antiquark annihilation ($\eta_g = 0$) and is clearly inconsistent with the data. The dash-dotted curve is for $\eta_g = 1$, using for the nucleon the gluon structure function from CDHS with $Q^2 = 9.6\ \mathrm{GeV}^2/c^2$ and for the pion the power $a = 3$ as predicted [17] by an extension of the counting rules.

We have studied also the sensitivity of the fit to different parameters and corrections. The correction for 30.5% χ contribution has caused an increase of 0.15 in the exponent a for the pion. An increase of 10% in the quark-antiquark contribution raises the value of a by about 0.01 *). When we increase the nucleon exponent b from 5 to 6 we find the pion exponent rises by 0.15. If we use for the nucleon the parametrization of CDHS [16] with $Q^2 = 9.6\ \mathrm{GeV}^2/c^2$, we find

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*) Our best fit is for zero quark-antiquark contribution, and with the CDHS function for the gluon in the nucleon it gives the value $a = 1.80$; for 50% contribution the best value is 1.84. We have estimated that the correction for ψ' decays increases the exponent a by 0.05. Hence the value quoted is 1.9.

almost the same results as when we take b = 5.3. Furthermore, increasing Q^2 by 1 GeV^2/c^2 increases our value of a by 0.04.

Fitting over the whole x region gives χ^2 of more than 50 for 10 degrees of freedom. Note that the error bars include only the statistical errors in the numbers of events observed and the statistical errors in the Monte Carlo. We see in fig. 3 that the measured maximum is shifted slightly to higher x than the fitted curve. Perhaps the x_1 dependence of the gluon structure function in the pion may have more detail than our simple parametrization allows, or the physics of J/ψ production may be more complicated than we have assumed. As a result of the large χ^2 of the fit, we give the largely systematic error of ±0.3 in the value of a. This error does not include uncertainty in the production model of J/ψ.

We conclude that thanks to good resolution and small background we have been able to determine the gluon structure function of the pion from the shape of the J/ψ longitudinal momentum distribution to be

$$(1-x_1)^{1.9\pm0.3} .$$

We have included a correction for the contribution of radiative χ decays. This result is only slightly affected by the fraction of J/ψ production through quark-antiquark annihilation, a quantity we are unable to determine independently. We have assumed that the QCD corrections to the J/ψ production give an x-independent correction to the gluon structure function of the pion; this remains to be proven. Thus the gluons in the pion are more energetic than predicted by the counting rules [17].

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Figure captions

Fig. 1 : The measured $\mu^+\mu^-$ invariant mass spectrum. Solid line: logarithmic scale; dashed line: linear scale.

Fig. 2 : a) The measured longitudinal momentum distribution of J/ψ. Solid line: raw data; dashed line: background.

b) The correction for χ decays; this multiplicative factor was applied to 30.5% of the events for each x bin.

c) J/ψ acceptance (%).

d) The precision in the measurements of x.

Fig. 3 : Corrected J/ψ x-distribution (data points). Solid curve: gluon-gluon fusion alone, with the gluon structure function of nucleon from CDHS and that of pion taken as $(1-x_1)^{1.9}$. Dash-dotted curve: gluon-gluon fusion alone; nucleon: CDHS, pion: $(1-x_1)^3$. Dashed curve: quark-antiquark annihilation alone. Inset: gluon structure function of pion $1.45\ (1-x_1)^{1.9}$ (solid line) with data points obtained assuming the CDHS gluon structure function for the nucleon (dashed line).

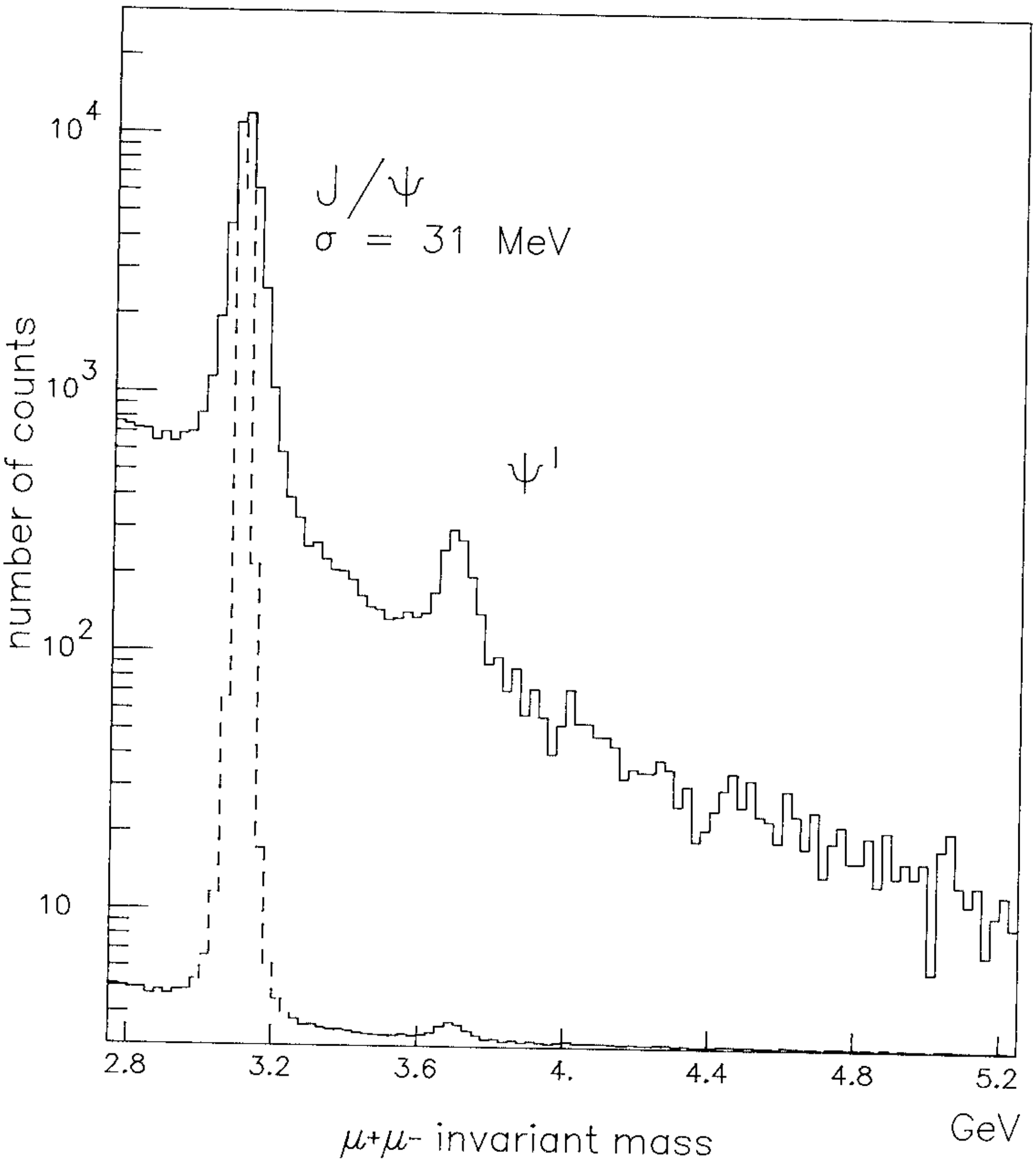
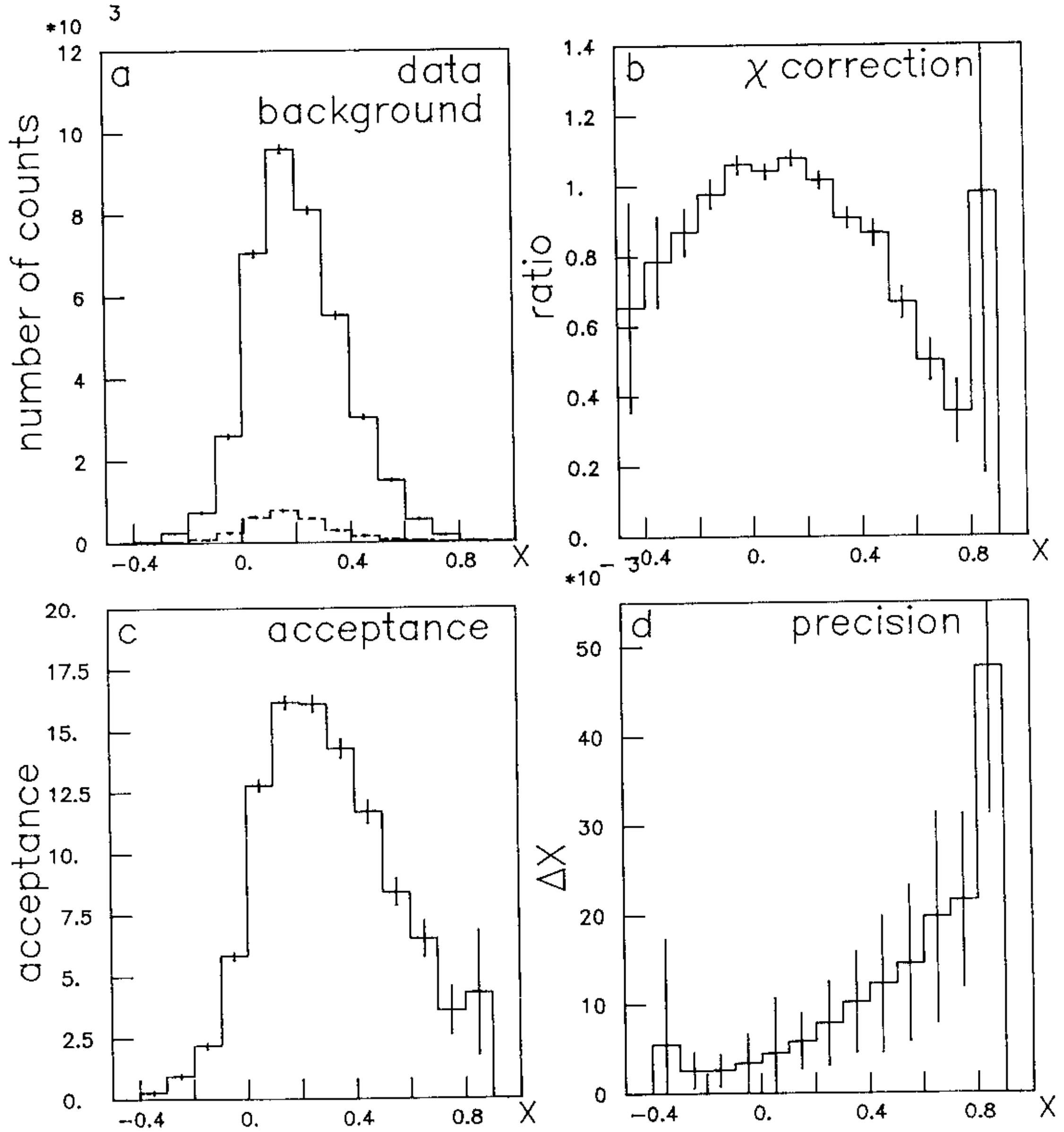

10^4
10^3
10^2
10
number of counts
J/ψ
σ = 31 MeV
ψ'
2.8
3.2
3.6
4.
4.4
4.8
5.2
GeV
$\mu^+\mu^-$ invariant mass

Fig. 1



J/ψ x distribution

Fig. 2

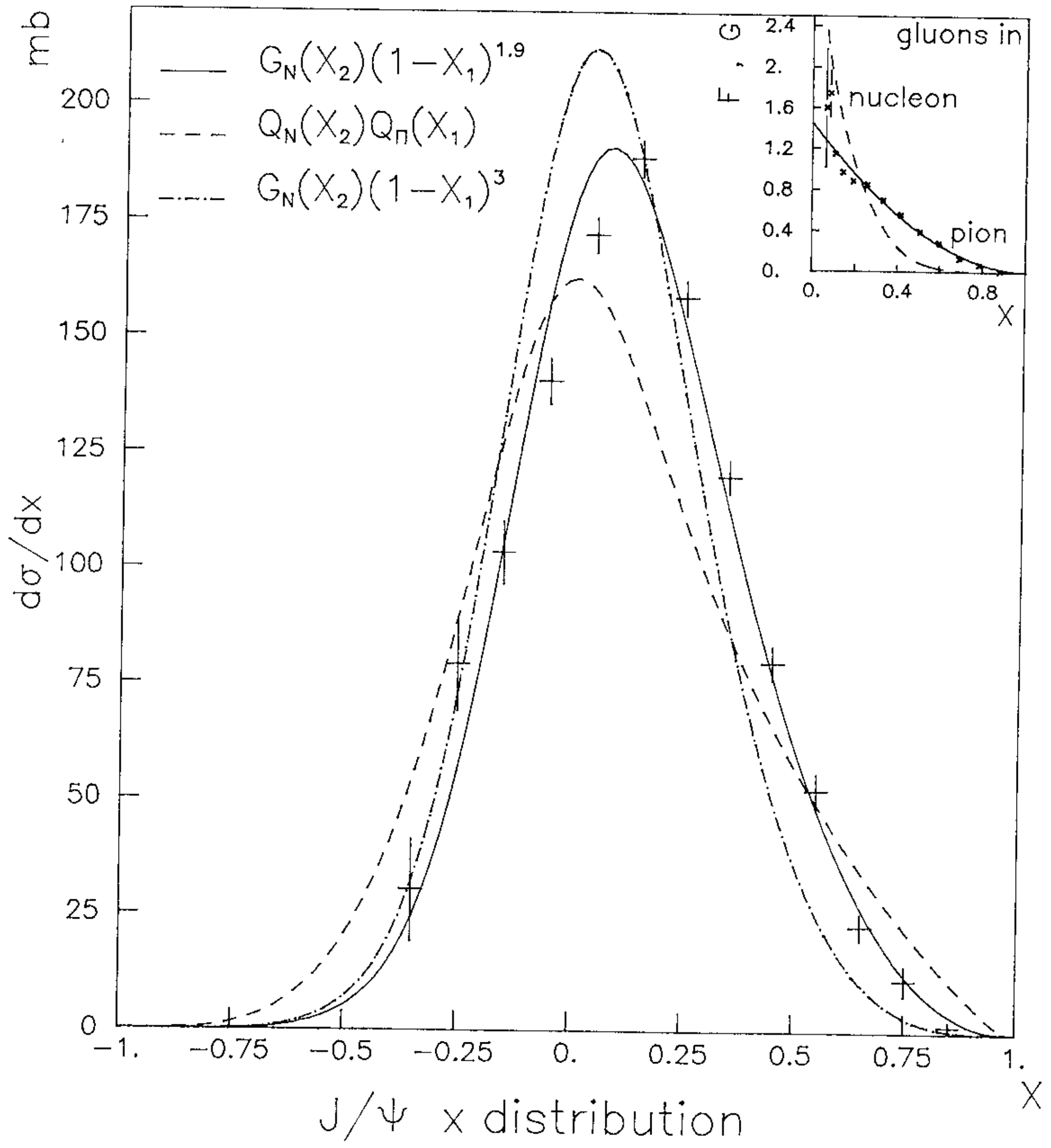

mb
dσ/dx
200
175
150
125
100
75
50
25
0
$G_N(X_2)(1-X_1)^{1.9}$
$Q_N(X_2)Q_\pi(X_1)$
$G_N(X_2)(1-X_1)^3$
gluons in
nucleon
pion
F , G
2.4
2.
1.6
1.2
0.8
0.4
0.
0.
0.4
0.8
X
−1.
−0.75
−0.5
−0.25
0.
0.25
0.5
0.75
1.
X
J/ψ x distribution

Fig. 3