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EXPERIMENTAL CROSS SECTION FOR DIMUON PRODUCTION

AND THE DRELL-YAN MODEL

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ABSTRACT

We have measured the absolute cross section for dimuon production in hadron collisions at 200 GeV/c in the continuum region $M = 4 - 8.5$ GeV. In all the channels studied (pN , $\bar{p}N$, π^+N and π^-H_2) the experimental cross section is significantly larger by a factor of 2.3 ± 0.5 than expected from the Drell-Yan model. Furthermore our proton-nucleon data allow a determination of the nucleon valence structure function which agrees with the deep inelastic lepton scattering data.

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1. INTRODUCTION

The absolute cross section of lepton-pair production in the high-mass continuum has attracted much theoretical interest recently. This is because the dimuon experiment possibly offers a sensitive test of higher order QCD corrections to the Drell-Yan process⁽¹⁾.

Here we discuss data on massive dimuon production in hadron collisions by different beam particles ($p, \bar{p}, \pi^\pm$) on platinum and on hydrogen targets. These results have been obtained by the NA3 spectrometer at the CERN SPS; experimental details and physics results have been published elsewhere⁽²⁻⁵⁾. Here we focus our attention to the question of the absolute cross section.

2. STATUS OF THE DRELL-YAN MODEL

In the Drell-Yan model lepton pairs are produced electromagnetically by $\bar{q}q$ annihilation into a massive virtual photon γ_v

The experiment measures the invariant mass $M_{\mu\mu}$ and $x_{\mu\mu}$ of the muon pair; the kinematic variables x_1 and x_2 are obtained through the relations

$$M_{\mu\mu}^2 = x_1 x_2 s \quad \text{and} \quad x_{\mu\mu} \equiv 2p_L^*/\sqrt{s} = x_1 - x_2 \quad (\text{transverse momentum effects are neglected})$$

The model has been tested through a number of specific predictions such as scaling ($M^3 d\sigma/dM = f(M/\sqrt{s})$), charge asymmetry (for example $\sigma(\pi^+N)/\sigma(\pi^-N) \rightarrow 1/4$ on an isoscalar target), and decay angular distribution ($d\sigma/d\cos\theta \propto 1 + \cos^2\theta$). These predictions have been verified in detail and the experimental data are in good agreement with the Drell-Yan model⁽⁵⁻⁸⁾.

As an additional test of the D.Y. model we have compared the dimuon production cross section on platinum and hydrogen targets used simultaneously.

The nuclear cross section on Pt($Z/A = 0.4$) has been written as

$$\sigma(\text{Pt}) = A^\alpha (0.4\sigma_p + 0.6\sigma_n)$$

where σ_p and σ_n are the cross sections on protons and neutrons respectively. The nuclear incoherence assumed in the D.Y. model implies $\alpha = 1$. We find $\alpha = 1.03 \pm 0.03$ in agreement with the model⁽⁹⁾.

With respect to the absolute cross section of lepton pair production new experimental evidence by the NA3 Collaboration demonstrates that the cross section is substantially larger than expected from the D.Y. model. A similar effect has also been seen in other experiments^(8,10).

The cross section of the D.Y. process is given by

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{3s} \cdot \frac{1}{3} \cdot \sum_i \frac{Q_i^2}{x_1^2 x_2^2} \{ f_i^h(x_1) f_{\bar{i}}^{h'}(x_2) + f_{\bar{i}}^h(x_1) f_i^{h'}(x_2) \} \quad (1)$$

where Q_i are the quark charges and $f_i(x_1)$, $f_{\bar{i}}(x_2)$ are the effective structure functions of the projectile and target particle respectively. The factor $1/3$ in equ.(1) allows for colour. The D.Y. model does therefore not contain any free parameter and the absolute value of the cross section is predicted exactly to the extent that both the projectile and target particle (i.e. their structure function) are known. This is the case for pN and $\bar{p}N$ where the nucleon structure function is known from deep inelastic scattering experiments.

Our present experimental data allow us to check these predictions in quantitative detail. If we express the ratio of the measured lepton pair cross section over the one expected from the D.Y. model by a scale factor K defined as

$$\left[\frac{d^2\sigma}{dx_1 dx_2} \right]_{\text{exp.}} = K \left[\frac{d^2\sigma}{dx_1 dx_2} \right]_{\text{D.Y. model}} \quad (2)$$

we find that $K = 2.3 \pm 0.5$ for all our reaction channels at 200 GeV/c : pN, $\bar{p}N$, π^+N and π^-H_2 .

It is the purpose of this paper to discuss the experimental evidence in detail.

3. RESULTS

3.1 Systematic error of the absolute cross section

In order to determine the absolute dimuon cross section we have calculated the absolute luminosity including all corrections on a selected subsample of our data. We then use the J/ψ signal as a relative monitor of the effective luminosity throughout the production runs.

The systematic error comes mainly from the following points :

- absolute calibration of the beam flux
- beam attenuation and re-interaction effects in the platinum target
- efficiency of the trigger system of the experiment
- losses and cuts in the off-line analysis of events
- estimation of the acceptance of our spectrometer from Monte Carlo computations.

Each item contributes 5 to 7%; therefore the total systematic error is estimated to be 15%.

For the J/ψ we find a cross section $B\sigma = 0.75 \pm 0.14 \mu\text{b}$ per Pt nucleus for $x > 0^{(2)}$ in agreement with previous experiments^{*)}.

For antiproton induced events, where the incoming antiproton is defined by a differential Cerenkov counter, an additional error must be added, which comes from efficiency corrections of the counter when used at high beam intensity ($4 \cdot 10^7$ particles per second). This error may be as large as 15% and the total systematic error on antiproton induced events is estimated at ~20%. The same error applies to the proton data where protons are identified by threshold Cerenkov counters.

The estimated contamination from ψ/ψ' events is less than 5% for the data with a mass cut at $4.0 \text{ GeV}(\pi^\pm \text{ and } \bar{p})$.

Fermi-motion of the nucleons in the target nuclei has a negligible effect on the integrated cross section.

*) For comparison we find for Anderson et al. ($\pi^- \text{C}$, 225 GeV/c)⁽⁹⁾ and Abolins et al. ($\pi^- \text{Be}$, 150 GeV/c)⁽¹¹⁾ $0.99 \pm 0.15 \mu\text{b}$ and $0.88 \pm 0.10 \mu\text{b}$ per Pt nucleus at 200 GeV/c when extrapolating their measured values with $\sigma \sim A^\alpha$, $\alpha = 0.93$ (average between NA3 and K.J. Anderson et al. ref 9) and taking into account the different beam momenta.

The contamination of muons from π and K decay as estimated from the measured mass spectrum of like-sign pairs is less than 1% for masses larger than 4 GeV.

3.2 The proton nucleon data

The practical use of the D.Y. mechanism to measure structure functions of unstable hadrons can be tested directly by comparing the proton structure function obtained from muon-pair production with that from deep inelastic lepton scattering (at equal $Q^2 = -M^2$). The large acceptance of our apparatus allows us to perform such a study since the shape of the x_1 and x_2 distributions can be determined independently. We make the assumption that the Buras-Gaemers parametrization⁽¹²⁾ can be used both for DIS and D.Y. processes (i.e. $Q^2 < 0$ and > 0).

We have obtained 960 proton induced dimuon events in the continuum above 4.2 GeV useful for a D.Y. type analysis; their mass distribution is shown in fig.1.

The structure function of the nucleon is extracted by fitting the (x_1, x_2) data sample to expression (1), with a Buras-Gaemers⁽¹²⁾ type of parametrization for the quark distribution functions. For the valence quarks we used :

$$\begin{aligned} u^p &= A_{\alpha\beta}^u x^\alpha (1-x)^\beta \quad \text{where} \quad \int \frac{u^p(x)}{x} dx = 2 \\ d^p &= A_{\alpha\beta}^d x^\alpha (1-x)^{\beta+1} \quad \text{where} \quad \int \frac{d^p(x)}{x} dx = 1 \end{aligned} \quad (3a)$$

The distributions for the sea quarks were taken to be :

$$\begin{aligned} \bar{u} &= \bar{d} = A_s (1-x)^{\beta_s} \\ \bar{s} &= 1/4(\bar{u} + \bar{d}) \end{aligned} \quad (3b)$$

The choice of the non-symmetric sea distribution was suggested by the results of the CDHS Collaboration⁽¹³⁾. The parameters left free in the fit were α , β and β_s since the valence functions (3a) were normalized to the respective number of quarks in the nucleon, while A_s is determined by fixing the total momentum fraction carried by valence and sea quarks to 50%.

TABLE 1

Results of the fit to the proton data

parameter	NA3	CDHS ⁽¹³⁾
α	0.5 ± 0.2	0.51 ± 0.02
β	3.2 ± 0.4	2.8 ± 0.1
$\langle u + d \rangle$	32%	34%
β_s	9.4 ± 1.0	8.1 ± 0.7
A_s	0.37	0.27
$\langle \text{sea} \rangle$	18%	15%

The results of the fit are shown in table 1, and are compared with the values of the parameters obtained by the CDHS fit at $Q^2 = -20 \text{ GeV}^2$ ⁽¹³⁾. This is the first determination of the valence nucleon structure function using high mass muon pairs produced in hadron collisions. There is good agreement between the D.Y. and the DIS determination of the nucleon structure function. This can also be seen from fig.2, where we show the projection onto the x_1 axis of our data, together with a curve resulting from the CDHS fit.

Using the nucleon parametrization as given in table 1, we can compute the absolute D.Y. cross section and compare it to our data. The result of our fit then yields $K = 2.4 \pm 0.4$, while the use of the CDHS fit gives $K = 2.2 \pm 0.4$. The K values are the same within errors as expected from the similarity of the input parameters.

3.3 The antiproton data

The weak point in determining K from pN data is the necessity of fixing the percentage of sea-quarks to the value found in the lepton scattering experiments, since dimuon production in pN reactions comes essentially from valence-sea terms.

The cleanest experimental way to obtain K is using antiprotons where the valence-sea terms are only a small contribution to the D.Y. cross section. We have evaluated the valence-valence contribution to the dimuon yield above 4 GeV which amounts to 84%, the valence-sea and sea-sea contribution are found to be 15.5% and 0.5% respectively.

The $\bar{p}$ experiment is however difficult and we have collected so far only 44 D.Y. events with $M > 4$ GeV, at 200 GeV/c on Pt. Their mass distribution is shown in fig.3.

Again using the CDHS parametrization we find for the $\bar{p}$ data : $K = 2.4 \pm 0.5$. Thus also the $\bar{p}N$ data indicate the same factor which in this channel cannot be explained by an increased sea as compared to DIS experiments.

3.4 The pion data on hydrogen

After the K factor was first found in our $\pi^\pm N$ data^(3,4) shown in fig.4, where $K = 2.2 \pm 0.3$ and 2.4 ± 0.4 for π^- and π^+ respectively, we have checked whether $K > 1$ could be due to coherent nuclear effects in the D.Y. process by measuring K directly on a 30 cm liquid hydrogen target. From the 138 π^- induced dimuon events with $M > 4$ GeV shown in fig. 5, we find $K = 2.4 \pm 0.4$.

When using the pion data to extract the K factor, the nucleon structure function is taken from the CDHS experiment⁽¹³⁾. The shape of the pion structure function is obtained from our data⁽⁴⁾ and its absolute normalisation is obtained by requiring the usual sum rule for the valence quark

$$\int \frac{f_u^-(x)}{x} dx = 1.$$

3.5 The $\pi^- - \pi^+$ data

We have also checked whether the "too large cross section" could be due to hadronic production of dimuons in the high mass continuum^{*)}, in addition to the D.Y. process. Such a background would contribute equally to π^+ and π^- induced events, and can therefore be eliminated by using the $\pi^- - \pi^+$ difference. This type of analysis has been done for the $\pi^\pm N$ data with the result that $K = 2.2 \pm 0.4$ in good agreement with the other channels.

4. SUMMARY AND CONCLUSIONS

In conclusion we have measured the absolute Drell-Yan cross section for p , $\bar{p}$, $\pi^\pm$ on Pt and π^- on H_2 targets at 200 GeV/c. The values of the experimental cross section factor K for the various reaction channels are summarized in table 2.

*) for instance via heavy particle decay.

TABLE 2

$$K = \frac{d^2\sigma}{dx_1 dx_2} \text{ exp.} / \frac{d^2\sigma}{dx_1 dx_2} \text{ D.Y.model}$$

Reaction	pN	$\bar{p}N$	$\pi^- N$	$\pi^+ N$	$\pi^- H_2$	$(\pi^- - \pi^+) N$
K	2.2±0.4	2.4±0.5	2.2±0.3	2.4±0.4	2.4±0.4	2.2±0.4
events	960	44	5607	2073	138	-

The errors quoted in table 2 take into account both the statistical and the systematic error of each individual channel, in addition there is an overall normalisation error of 15% common to all channels.

The ratio of $\sigma^{(\text{expt.})}/\sigma(\text{D.Y.})$ is the same within errors for all reactions and has an average value of $K = 2.3 \pm 0.5$ (systematic error). K is roughly mass independent within statistics as can be seen from the shape of our mass spectra (fig. 1 and 4). Furthermore our nucleon valence structure function is similar in shape to the result of CDHS (fig.2).

We have shown that the effect cannot be explained by :

- i) a non-linear A-dependence (H_2 data)
- ii) an increased sea ($\bar{p}N$ data)
- iii) a hadronic source of dimuons ($\pi^- - \pi^+$ data).

It is therefore possible that we see here an experimental manifestation of QCD corrections to the D.Y. process as expected by theory. The approximate numerical agreement with the first order QCD correction may however be fortuitous, since higher order corrections have not yet been calculated and could be large, too (for a review of theoretical predictions see ref.14).

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- (9) Making use of the measured cross section difference $\sigma^{\pi^-} - \sigma^{\pi^+}$ in order to eliminate sea effects and using the D.Y. model we can write

$$A \frac{(\sigma^{\pi^-} - \sigma^{\pi^+}) \text{ on H}_2}{(\sigma^{\pi^-} - \sigma^{\pi^+}) \text{ on Pt}} = 1.51 \pm 0.28 = A^{1-\alpha} \frac{4u-d}{u+2d}, \text{ where}$$

$$\frac{4u-d}{u+2d} = \begin{cases} 1.75 & \text{for } u = 2d, \text{ or} \\ 1.80 & \text{for } d/u = 1.125(1-x) \text{ at } \langle x \rangle_{\text{expt}} = 0.15 \end{cases}$$

Concerning the so-called "A-dependence"

previous experiments have found contradictory results. The CFS Collaboration⁽⁷⁾ found $\alpha = 1.02 \pm 0.02$ in pN collisions. The CIP Collaboration found $\alpha = 1.12 \pm 0.05$ for π^-N collisions, see

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Since we need parametrizations of u and d separately and CDHS gives a parametrization of u + d, we determine α and β assuming $\alpha_u = \alpha_d$, $\beta_d = \beta_u + 1$ and the equality of 2nd and 3rd moments:

$$M_{u+d}(2) = M_u(2) + M_d(2)$$

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FIGURE CAPTIONS

- Fig. 1 Dimuon mass spectrum for pN events at 200 GeV/c. The data are compared to predictions from the D.Y. model using the CDHS nucleon structure function.
- Fig. 2 The proton structure function as derived from pN data compared to CDHS results at $|Q^2| = 20 \text{ GeV}^2$.
- Fig. 3 $\bar{p}$ induced dimuon mass spectrum at 200 GeV/c compared to the expectation from the D.Y. model using CDHS data.
- Fig. 4 Dimuon mass spectrum in the reactions $\pi^\pm N$ at 200 GeV/c; the data are compared to predictions with the CDHS nucleon parameters as input.
- Fig. 5 Dimuon mass spectrum for $\pi^- H_2$ data at 200 GeV/c, compared to predictions from the D.Y. model using the CDHS nucleon parameters as input.

FIG.1

FIG.2

FIG. 3

FIG. 4

FIG.5