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DIFFRACTION DISSOCIATION OF HIGH ENERGY PROTONS IN p-d INTERACTIONS*

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We report results from a measurement of the inclusive process $p + d \rightarrow X + d$ n the region $0.03 < |t| < 0.12 (\mathrm{GeV}/c)^2$ and $5\ \mathrm{GeV}^2 < M_X^2 \lesssim 0.11\ p_{lab}$ for ncident proton momenta from 150 to 400 GeV/c. We find that in this region, he differential cross section $d^2\sigma/dtdM_X^2$ varies only slowly with energy, alls exponentially with $|t|$, and behaves to a good approximation as $1/M_X^2$. he measurement was performed at Fermilab by detecting slow recoil deuterons rom a deuterium gas jet target placed at the internal beam of the accelerator.

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As part of an experimental study[1,2] of the low four momentum transfer interaction of high energy protons with a deuterium gas jet target in the internal beam at Fermilab, we have measured the differential cross section $d^2\sigma/dtdM_x{}^2$ for the inelastic inclusive reaction

$$p + d \rightarrow X + d \tag{1}$$

in the region $0.03 < |t| < 0.12$ $(GeV/c)^2$ and $(5\ GeV^2/s) < (M_x{}^2/s) \lesssim 0.03$, where $s \approx 2m_d\ p_{lab}$, for incident proton momenta from 150 to 400 GeV/c. In this region of small $|t|$ and small $M_x{}^2/s$ reaction (1) is expected to be dominated by diffraction dissociation of the incoming proton. Results on the excitation of protons into the resonance region ($M_x{}^2 < 5\ GeV^2$) are presented in a separate letter[2]. Here we discuss the diffraction dissociation of protons into the continuum of states with $M_x{}^2 > 5\ GeV^2$, up to $M_x{}^2/s \approx 0.03$ or $M_x{}^2 \sim 40\ GeV^2$ for our highest proton momentum.

The apparatus and experimental technique are described in detail in references 1 and 2. A deuterium gas jet was pulsed to intercept the internal beam at predetermined times during the acceleration cycle, thus selecting the desired beam momenta. The FWHM of the jet at beam height was $\sim$1.2 cm. Slow recoil deuterons were detected by stacks of two surface barrier silicon solid state detectors placed on a movable carriage at a distance 2.5 m from the target near 90^0 to the beam. The size of the detectors, which were collimated to a circular area of $\sim 1\ cm^2$, and the width of the jet, result in an angular resolution for the recoils of about ±3 mrad. The thickness of the front detector in each stack was 0.2 mm and that of the rear detector either 1.5 or 5 mm. Since only those recoils that stop in the rear detector were accepted, deuterons were identified unambiguously by measuring their energy loss in each detector.

The t-value is obtained from the measured kinetic energy T of the deuteron, $|t| = 2m_d T$. The scaling variable x, defined as $p_{\parallel}/p_{max}$ of the deuteron in the c.m. system, is given by

$$1 - x \simeq \frac{M_x^2 - m_p^2}{s} \simeq \frac{\sqrt{|t|}}{m_d} \left(\sin\omega - \frac{\sqrt{|t|}}{2m_d}\right) \qquad (2)$$

where ω is the recoil angle measured from 90°. For a given $|t|$, a detector placed at an angle ω samples the same x region (or, for large M_x^2, the same M_x^2/s region) independent of the incident proton momentum. In this experiment, the angle ω was kept $\lesssim 17°$ corresponding to $x \gtrsim 0.97$ or $M_x^2/s \lesssim 0.03$. The mass M_x^2 is calculated using equation (2). The resolution in M_x^2 is dominated by the uncertainty in the recoil angle, $\Delta M_x^2 = 2\, p_{lab} \sqrt{|t|}\, \Delta\omega$. Over the range of t and p_{lab} covered by the data in this report, ΔM_x^2 varies from 0.15 to 0.8 GeV^2.

The counts ΔN within a t interval $\Delta|t| = 2m_d \Delta T$ registered in a detector stack at an angle ω were converted to absolute differential cross sections $d^2\sigma/dtd(M_x^2/s)$ by normalizing to elastic scattering[1,2] with a detector stack fixed at a small angle ω. At each s value, the normalization uncertainty was estimated to be about ±3%. The statistical errors, typically a few percent, were combined in quadrature with a 1% systematic error, which is the estimated uncertainty in the area calibration of the detectors and the fluctuation of dead time losses during the experiment[1]. A background of recoil deuterons was observed in the unphysical region $M_x^2 < m_p^2$. The measured level was $\sim 3\times 10^{-4}$ of the elastic counts at the same value of $|t|$, independent of angle over the range of angles at which it could be observed. This behavior is consistent with that to be expected in our apparatus from rescattering of elastic deuteron recoils. This background is adequately fit by

$$\left.\frac{d^2\sigma}{dt\,d(M_x^2/s)}\right|_{\text{background}} = (19\pm3)\ e^{-(30\pm12)\ (|t|\ -\ 0.05)}\ \text{mb}\cdot(\text{GeV/c})^{-2} \qquad (3)$$

This correction, which varies between 3% and 15%, has been applied to the data.

Typical differential cross-sections for fixed M_x^2 are shown in Figure 1. These cross-sections exhibit a steep t-dependence as expected for coherent scattering from deuterons. Within the range of M_x^2 covered in this experiment, we find no evidence for a turnover in the t-distributions down to values of $|t| \approx 0.03$. Guided by p-d elastic scattering[1], we have fitted the differential cross-sections with the form

$$\frac{d^2\sigma}{dt\,dM_x^2} = a\ (s,M_x^2)\ \ e^{-b(s,M_x^2)\ (|t|-0.05)\ +\ c\ (t^2-0.05^2)} \qquad (4)$$

where c was kept fixed at 62.3 $(\mathrm{GeV}/c)^{-4}$. This value was taken from the deuteron form factor[3] as determined in p-d elastic scattering[2]. The fit was made around the central value of our measured t-range so that the best fit values and errors of a and b remain uncorrelated. The lines in Figure 1 are the best fits to the data using this formula.

The results of the fits for $a(s,M_x{}^2)$ and $b(s,M_x{}^2)$ are given in Table I. In figure 2a, we show $b(s,M_x{}^2)$ as a function of $M_x{}^2$. Within errors, it is independent of energy and of $M_x{}^2$. A one parameter fit to all the $b(s,M_x{}^2)$ values yields $b = 32.9 \pm 0.3\ (\mathrm{GeV}/c)^{-2}$ with $\chi^2 = 1.33$ per degree of freedom. The values of $a(s,M_x{}^2)$ multiplied by $M_x{}^2$ are plotted in Figure 2b. It is apparent that $d^2\sigma/dtdM_x{}^2$ behaves predominantly as $1/M_x{}^2$. A fit of our data to the form

$$\left.\frac{d^2\sigma}{dtdM_x{}^2}\right|_{|t| = 0.05} = \frac{D(s)}{(M_x{}^2)^{\alpha(s)}} \qquad (5)$$

yields the following results:

P_{lab} GeV/c	s GeV^2	D(s) $\mathrm{mb}\cdot(\mathrm{GeV}/c)^{-2}\cdot(\mathrm{GeV})^{2\alpha(s)-2}$	$\alpha(s)$	χ^2/d.f.
150	567	4.38 ± 0.33	1.068 ± 0.035	1.10
		3.784 ± 0.035	1	1.43
275	1035	3.63 ± 0.17	1.028 ± 0.019	0.83
		3.391 ± 0.030	1	0.93
385	1448	3.19 ± 0.15	1.004 ± 0.017	1.90
		3.157 ± 0.023	1	1.77

The values of $\alpha(s)$ obtained from the fit are consistent with unity. The values of $D(s)$ listed in the second row at each energy were obtained by setting $\alpha(s) = 1$ in eq. (5) and making a one parameter fit. This simple $1/M_x^2$ fit is statistically acceptable and corresponds to the lines drawn in Figure 2b. It must be pointed out that the $1/M_x^2$ behavior for the cross section at fixed t does not hold if the M_x^2 range is extended to include the resonance region. This is illustrated in Figure 3 where we have plotted our data together with the data[2] for $M_x^2 < 4$ GeV^2 for 275 GeV/c. The deviation of the low mass data from the $1/M_x^2$ form is larger at the smaller t value.

The errors in $D(s)$, equation 5, do not include the normalization uncertainty of $\pm 3\%$ mentioned previously. Taking this uncertainty into account, we have made a fit of all our data to the form

$$\left.\frac{d^2\sigma}{dt\,dM_x^2}\right|_{|t| = 0.05} = A\left(1 + \frac{B}{p_{lab}}\right) \frac{1}{M_x^2} \qquad (6)$$

We find $A = 2.80 \pm 0.16$ mb$\cdot$(GeV/c)$^{-2}$ and $B = 54 \pm 16$ (GeV/c) with $\chi^2 = 47$ for 35 degrees of freedom. The cross section at any t value in our range, obtained from (6) and (4) using the fitted slope $b = 32.9 \pm 0.3$ (GeV/c)$^{-2}$, is given by

$$\frac{d^2\sigma}{dt\,dM_x^2} = \left[\frac{(3.50 \pm 0.20)}{M_x^2} \left(1 + \frac{54 \pm 16}{p_{lab}}\right) e^{-(6.5 \pm 0.3)\,|t|}\right] F_d(t) \qquad (7)$$

Here $F_c(t)$ is the coherence factor defined[2] as

$$F_d(t) = \left(\frac{\sigma_\tau^{pd}}{\sigma_\tau^{pp}}\right)^2 \left|S(t)\right|^2 \qquad (8)$$

where σ_τ is the total cross section and $S(t)$ is the deuteron form factor[1]. We have used $(\sigma_\tau^{pd}/\sigma_\tau^{pp})^2 = 3.6$ and[1] $|S(t)|^2 = e^{-26.4|t| + 62.3\,t^2}$. In eq. 7, we have purposely factorized the coherence factor in order for the term in the bracket to represent the cross section for the diffraction dissociation of the proton per nucleon. As is the case with elastic scattering, the Glauber corrections are not expected to modify the slope of 6.5 ± 0.3 $(\mathrm{GeV/c})^{-2}$ by more than one unit. Our extracted nucleon-nucleon data for $M_x^2 < 4$ GeV^2 agree very well[2] with data from $p + p \to X + p$. A similar direct comparison for $M_x^2 > 5$ GeV^2 is not possible at present due to lack of experimental data for $pp \to Xp$ at small values of t.

We are grateful to many members of the Fermilab staff and in particular to the personnel of the Internal Target Section for their cooperation in the planning and execution of this experiment. We acknowledge the support of the technical staff at Rockefeller University and the University of Rochester. The Soviet members of our team express their gratitude to the State Committee for Atomic Energy of the USSR and the JINR, Dubna, for their generous support.

REFERENCES

1. Y. Akimov, et al., Proton-Deuteron Elastic Scattering at Small Momentum Transfer from 50 to 400 GeV/c, submitted for publication to Phys. Rev. D, preprint

2. Y. Akimov, et al., Phys. Rev. Letters (preceding letter)

3. This is justified by the near factorization of the form factor in elastic scattering (Ref. 1) and by the factorization of the diffractive vertex in the low mass region (Ref. 2). In a fit of our inelastic data where c was treated as a free parameter, we obtained $c = 64.3 \pm 11.4\ (\mathrm{GeV}/c)^{-4}$ in agreement with the (more accurate) value of 62.3 ± 1.1 given by the deuteron form factor.

Differential Cross Sections at $|t| = 0.05$ and Slope Parameter[a] for $p + d \to X + d$

P_{lab}	150 GeV/c		275 GeV/c		385 GeV/c	
M_X^2	$\left.\frac{d^2\sigma}{dtdM_X^2}\right\|_{\|t\|=0.05}$	b	$\left.\frac{d^2\sigma}{dtdM_X^2}\right\|_{\|t\|=0.05}$	b	$\left.\frac{d^2\sigma}{dtdM_X^2}\right\|_{\|t\|=0.05}$	b
$(GeV)^2$	$mb\cdot(GeV/c)^{-2}\cdot GeV^{-2}$	$(GeV/c)^{-2}$	$mb\cdot(GeV/c)^{-2}\cdot GeV^{-2}$	$(GeV/c)^{-2}$	$mb\cdot(GeV/c)^{-2}\cdot GeV^{-2}$	$(GeV/c)^{-2}$
5.5	0.700 ± 0.019	33.5 ± 2.4	0.635 ± 0.025	37.0 ± 3.3		
6.5	0.600 ± 0.010	34.7 ± 0.8	0.538 ± 0.010	32.6 ± 1.3	0.580 ± 0.057	25.1 ± 13.4
7.5	0.528 ± 0.013	30.4 ± 1.1	0.451 ± 0.009	34.0 ± 1.2	0.432 ± 0.010	37.3 ± 1.9
8.5	0.425 ± 0.011	32.9 ± 2.4	0.416 ± 0.015	35.1 ± 1.6	0.364 ± 0.008	32.0 ± 1.6
9.5	0.394 ± 0.007	33.0 ± 0.9	0.340 ± 0.011	35.3 ± 3.1	0.341 ± 0.005	34.6 ± 1.1
11.	0.335 ± 0.006	30.7 ± 1.0	0.307 ± 0.007	33.8 ± 1.0	0.293 ± 0.006	33.5 ± 1.0
13.	0.294 ± 0.010	31.5 ± 1.2	0.252 ± 0.015	33.1 ± 4.9	0.229 ± 0.004	32.8 ± 1.6
15,	0.243 ± 0.020	28.5 ± 2.9	0.217 ± 0.007	33.3 ± 2.9	0.214 ± 0.005	30.5 ± 1.1
17.			0.201 ± 0.005	34.3 ± 0.9	0.188 ± 0.005	31.3 ± 1.5
19.			0.177 ± 0.011	27.3 ± 8.2	0.167 ± 0.005	35.8 ± 2.8
22.			0.154 ± 0.005	31.9 ± 1.1	0.137 ± 0.003	34.8 ± 1.9
26.			0.126 ± 0.012	27.7 ± 4.5	0.125 ± 0.003	33.1 ± 1.4
30.					0.109 ± 0.004	33.1 ± 2.1
34.					0.101 ± 0.007	30.5 ± 1.8
38.					0.090 ± 0.020	28.9 ± 8.2

(a) See eq. 4 in text.

FIGURE CAPTIONS

Figure 1 - Differential cross-sections $d^2\sigma/dtdM_X^2$ ($p + d \to X + d$) versus t for fixed M_X^2 (p_{lab} = 275 GeV/c). The lines are best fits to the data using eq. (4) of the text.

Figure 2 - Fitted values for $p + d \to X + d$ plotted versus M_X^2 for p_{lab} = 150, 275, and 385 GeV/c.

(a) The slope parameter $b(s,M_X^2)$ as obtained from the fit

$$d^2\sigma/dtdM_X^2 \sim e^{-b(s,M_X^2)|t| + 62.3\ t^2}$$

(b) Differential cross-sections

$d^2\sigma/dtdM_X^2$ at $|t| = 0.05$ multiplied by M_X^2.

Figure 3 - Differential cross-sections versus M_X^2 for t = 0.035 and t = 0.05 for p_{lab} = 275 GeV/c. Data for $M_X^2 < 4\ GeV^2$ are from ref. 2.

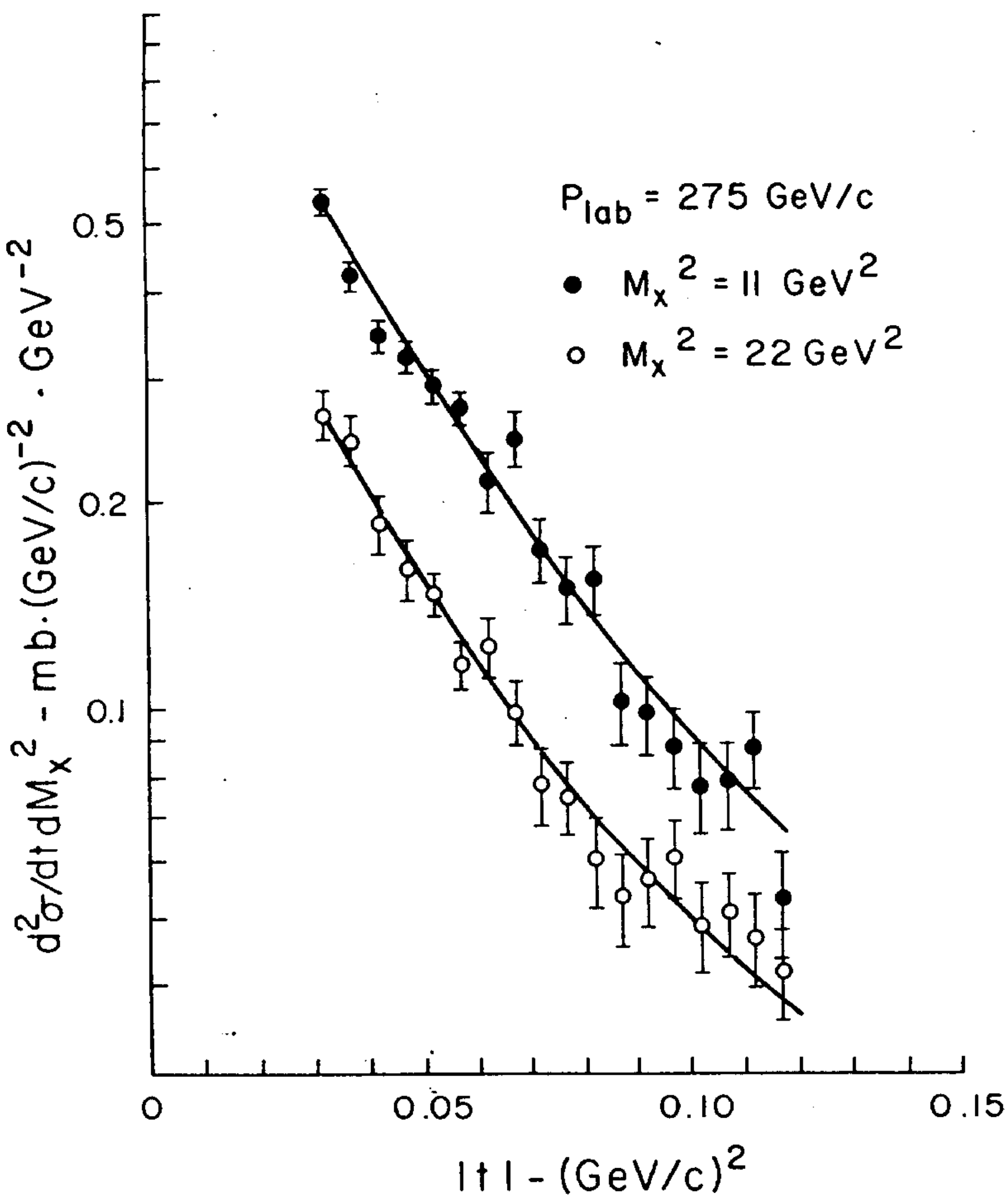
P_lab = 275 GeV/c
● M_x 2 = 11 GeV2
○ M_x 2 = 22 GeV2
d2σ/dt dM_x 2 - mb·(GeV/c)-2 · GeV-2
0.5
0.2
0.1
0
0.05
0.10
0.15
|t| - (GeV/c)2

Fig. 1

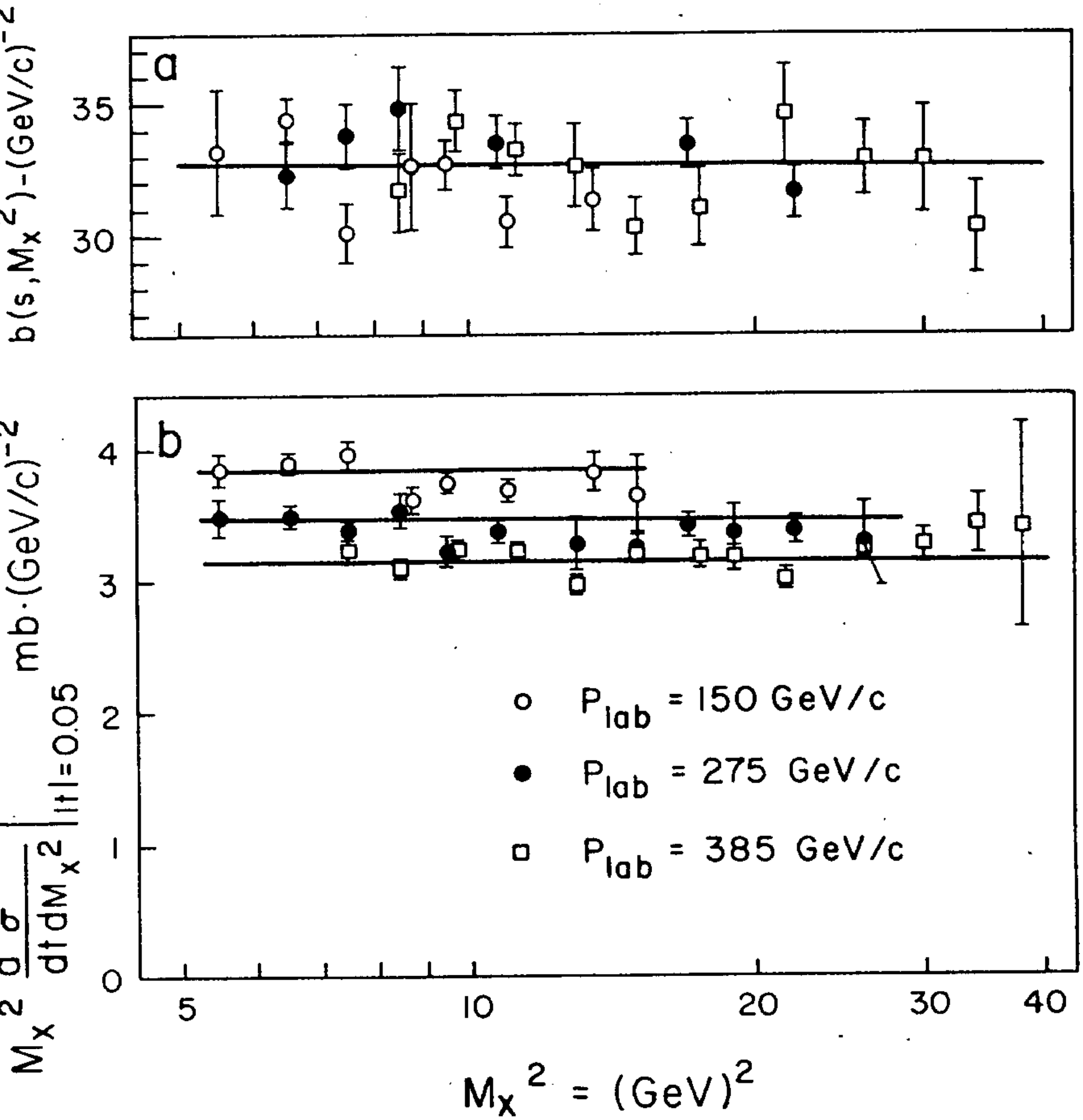
a
b
35
30
$b(s,M_x^2)$-$(GeV/c)^{-2}$
4
3
2
1
0
$M_x^2 \frac{d^2\sigma}{dt\,dM_x^2}\Big|_{|t|=0.05}$ mb·$(GeV/c)^{-2}$
○ P_{lab} = 150 GeV/c
● P_{lab} = 275 GeV/c
□ P_{lab} = 385 GeV/c
5
10
20
30
40
$M_X{}^2$ = $(GeV)^2$

Fig. 2

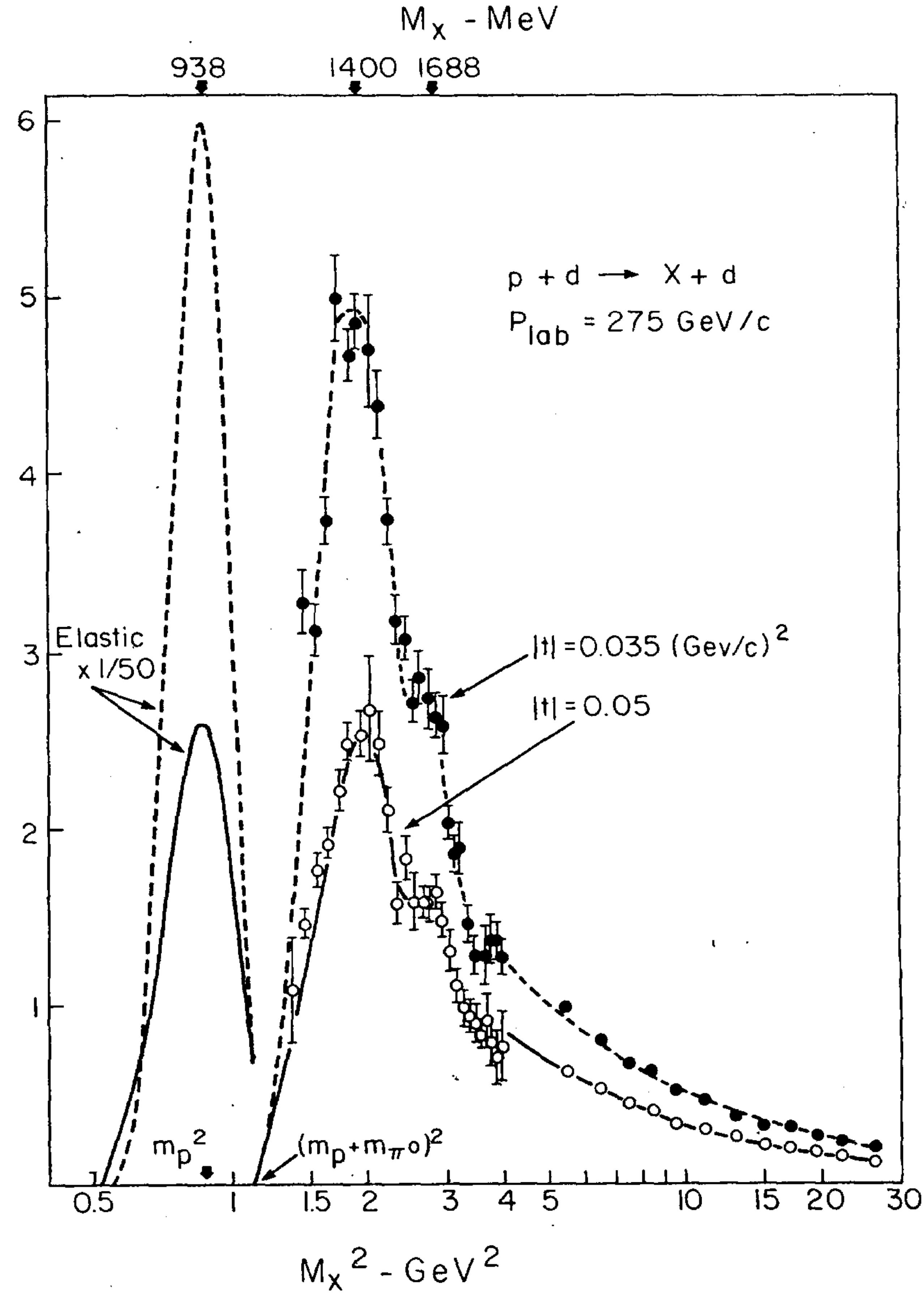
Mx - MeV
938
1400
1688
6
5
4
3
2
1
p + d → X + d
Plab = 275 GeV/c
Elastic
x 1/50
|t| = 0.035 (Gev/c)²
|t| = 0.05
mp²
(mp+mπo)²
0.5
1
1.5
2
3
4
5
10
15
20
30
Mx² - GeV²

Fig. 3

Erratum: Proton-Deuteron Elastic Scattering at Small Momentum Transfer from 50 to 400 GeV/c

[Physical Review D12, 3399 (1975)]

Y. Akimov, L. Golovanov, S. Mukhin, A. Sandacz, G. Takhtamyshev, V. Tsarev, E. Malamud, R. Yamada, P. D. Zimmerman, R. Cool, K. Goulianos, H. Sticker, D. Gross, A. Melissinos, D. Nitz, and S. Olsen

There is a computational error in the differential pd elastic cross sections given in Table III. They should be corrected as follows:

P_{LAB} (GeV/c)	Multiply the cross section and its error by
49	0.9811
72	0.9371
148	0.9688
174	0.8589
221	0.8674
248	0.9722
270	0.8976
289	0.8751
346	0.8785
384	0.9038

None of the results of the fits are affected by this error.

In Eq. (12) the term $f_c(t)$ should read $f_c^2(t)$.