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Proton-Proton Inelastic Scattering at 0.5 TeV*

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ABSTRACT

During a few hours of operation of the Fermilab Accelerator at 500 GeV we have measured the cross section $d^2\sigma/dt\, dM_X^2$ for the inclusive reaction $p + p \rightarrow p + X$. We determine the mass spectrum of the diffractive peak to be $1/M_X^{3.8 \pm 0.2}$ and the scaling part of the cross section to be $d\sigma/dM_X^2 = (15.7 \pm 1.1)/s$ mb/GeV^2.

On May 14th, 1976, the Fermilab Accelerator achieved the new record energy of 500 GeV. We were able to study the inclusive inelastic reaction $p + p \rightarrow p + X$ by interacting the coasting 500 GeV beam with a H_2 jet target. The beam was available for four and a half hours at an intensity of $\simeq 10^{12}$ protons per turn, or 5×10^{15} protons on target per machine cycle. We define the usual parameters for an inclusive reaction: t, the square of the four momentum transfer to the recoil proton, and M^2, the energy of X in its rest frame. In the run reported here we covered major portions of the range $0.017 < -t < 0.249$ $(GeV/c)^2$ and $6.25 < M^2 < 187$ GeV^2, with the higher mass values being measured mostly at the higher $|t|$ values. The inclusive $pp \rightarrow pX$ reaction has been studied extensively by us at Fermilab[1] up to $s = 750$ GeV^2 and from $s = 549$ to $s = 3892$ GeV^2 at ISR[2] where s is the total center of mass energy squared. The results presented here at $s = 940$ GeV^2 are particularly valuable to establish comparisons between the completely different experimental methods because they greatly extend the range of energy overlap, thus giving a more complete picture of the energy dependence of the cross section.

Recent progress[3] in the understanding of inelastic diffraction has led to speculations that this process is peripheral in impact parameter space, and therefore the canonical value of $\sigma_{diff} = 6\text{-}9$ mb saturates the Pumplin bound.[4] However, there are ambiguities on how the inelastic diffractive cross section might be extracted from the measured inelastic cross section and about its structure in M^2. It has become accepted, for convenience's sake, that the measured cross section integrated up to $M^2 = 0.1s$ is the magnitude of the singly diffractive cross section. We will show that the

inclusive inelastic cross section in fact has an energy independent term and a scaling term. Since a diffractive cross section should be essentially energy independent, we propose that it is the former term which measures it. We obtain: $\sigma_{diff} = 2 \times (1.87 \pm 0.16)$ mb. In addition, we conclude that the M^2 structure is different from that predicted by triple-Regge arguments.[5] In particular, the contribution of the triple Pomeron is negligible.

The present experiment measures a very wide range in M^2 with good energy resolution and a t range which contains ≃ 70% of the cross section. The equipment was designed to obtain very precise data on inelastic processes. We were therefore able to obtain significant information at 500 GeV while operating at an integrated luminosity of ≃ 1/100th of a standard run. The experiment is performed at the Fermilab Internal Target Area by interacting the circulating beam with a hydrogen jet target. Our target was especially designed to obtain a very collimated jet. We typically operate with a source size of 1.5 mm f.w.h.m. and a luminosity of 10^{34} $cm^{-2}sec^{-1}$ for 10^{13} circulating protons. Recoil protons are detected by telescopes with angular acceptance $\Delta\theta$ = 4mm/750mm = 5.3 mrad. A stack of two surface barrier silicon detectors in each telescope identifies protons and measures their kinetic energy in the range $10 < T < 125$ MeV. Seven telescopes on a moveable carriage cover the angular range $48^\circ < \theta < 90^\circ$. A fixed telescope at 83.5°, where the maximum of $d\sigma_{el}/d\cos\theta$ is located, measures the jet-beam luminosity (we use σ_{el} = 7.2 mb at 500 GeV). Between telescopes and interaction point is placed an anti counter which allows each telescope to view a circle of ≃ 8 mm r.m.s. radius

around the beam-jet intersection point. Thus most solid matter surrounding the extremely thin target ($\simeq 2 \times 10^{-8}$ gr/cm^2) is shielded from the telescopes. We have achieved background levels $\simeq 10^6$ times smaller than the elastic signal and $\lesssim$ 2% of the smallest inelastic cross section measured. Recoil protons are analyzed in real time, producing directly a 3-dimensional mapping of $d^2\sigma(s)/dT\, d\cos(\theta)$.[6]

The cross section measured at 500 GeV is shown plotted vs. M^2, for 6 values of t, in Fig. 1. No corrections were applied to any data since we estimate them to be well below the statistical accuracy. The expression $a + b/(M^2)^\alpha$ was fitted to each spectrum with a, b, α as free parameters. The values for α were all in the interval 1.7 to 2.1, with errors $\lesssim$ 20%. Averaging all six values we obtain $\alpha = 1.9 \pm 0.13$. We therefore refitted all data to the form $a + b/(M^2)^{1.9}$, the results of these fits are shown in Fig. 1. The combined χ^2 for all six fits is $\chi^2 = 61$ for 81 degrees of freedom. For comparison, a fit to the form $a + b/M^2$ gives $\chi^2 = 117$ corresponding to a confidence level of 10^{-5}. We wish also to remark that fits to the standard triple-Regge formulae always lead to a negative value for the square of the PPR coupling,[5] a consequence of the sharp fall at low M^2 and the constant cross section at high mass.

At $|t|$ values higher than included in Fig. 1, we only measured masses larger than 60 GeV^2. We show in Fig. 2 the average value of $d^2\sigma/dtdM^2$ versus t for $M^2 > 60$ GeV^2. Also shown is a fit to the data of a simple exponential $a \times \exp(bt)$, resulting in $d^2\sigma/dtdM^2 = (0.104 \pm 0.006)\exp((6.3 \pm 0.4)t)$ mb/GeV^4. The value of the slope parameter $b = 6.3 \pm 0.4$ is in excellent agreement with the values

reported by the CHLM[2] collaboration at ISR. Also from this fit we obtain $d^2\sigma/dtdM^2(t = -0.25(\mathrm{GeV}/c)^2) = 0.0215 \pm 0.0011$ mb/GeV^4, to be compared with the value 0.0224 ± 0.0033 mb/GeV^4 obtained averaging the ISR data for $62 < M^2 < 94$ GeV^2 at $s = 934$ GeV^2.

To study the question of the energy dependence we integrate over t all collected data and incorporating s in the first term, we obtain $d\sigma/dM^2 = (14.3 \pm 1)/s + (3.4 \pm 1)/M^{3.8\pm0.2}$mb/GeV^2. The result for the scaling term 14.3/s agrees with our previous result[7] of $(14.7 \pm 0.7)/s$ obtained for $260 < s < 750$ GeV^2. Since CHLM reports a constant value of $sd\sigma/dM^2$ at high masses, our result agrees with their measurements up to $s = 2000$ GeV^2 to better than 10%.

The magnitude of the energy independent term is relatively less well determined by the present data since 65% of its contribution is from $M^2 < 6.5$ GeV^2 and an extrapolation was performed to reach the inelastic threshold $M^2 \simeq 2$ GeV^2. In two previous experiments[1] we have shown that the inelastic spectrum cuts sharply below $M^2 = 2$ to 2.2 GeV^2 and falls rapidly to zero well above the kinematic threshold. Integration of $d\sigma/dM^2$ yields $\sigma(pp \to pX,\ 2 < M^2 < 0.1s) = (1.4 \pm 0.1) + (1.96 \pm 0.58) = 3.36 \pm 0.59$ mb. Previously we obtained (for $260 < s < 750$ GeV^2) $\sigma(pp \to pX,\ 2 < M^2 < 0.1s) = 3.1 \pm 0.1$ mb independent of s. The two values are clearly in agreement; we will use the better determined value in later calculations. The M^2 dependence ($\simeq 1/M^4$) found in this experiment is in good agreement with our previous findings. The sharp drop in M^2 is also quite evident in bubble chamber experiments from 60 to 400 GeV.[8]

The CHLM experiment reports[2] instead a spectrum like $1/M^2$.

However both our integrated and high mass cross sections agree very well with their results. We therefore suggest that the different shape observed at ISR is due to the wider M^2 resolution of their experiment. Dimensional arguments furthermore suggest for the energy independent cross section $d\sigma/dM^2 = \text{const}/M^4$. Similarly, for the scaling term the only scale is fixed by σ_{tot}, resulting in $d\sigma/dM^2 = g(M^2/s) \times \sigma_{tot}/s$ where $g(M^2/s)$ appears to be remarkably constant up to $M^2/s = 0.15$. It is therefore logical that the inelastic spectrum should be of the form $d\sigma/dM^2 = A/s + B/M^4$.

The t integrations mentioned previously were performed assuming a constant logarithmic slope parameter $b = 6.3$, as measured. Since the slope has been measured[2] to decrease at high $|t|$ for large M^2, the correct values for those integrals are 10% higher. We shall therefore use $\sigma = 3.41 \pm 0.11$ mb for the inclusive cross section up to $M^2 = 0.1s$, and $d\sigma/dM^2 = (15.7 \pm 1.1)/s$ mb/GeV^2 for the scaling part. We can finally determine the value of the energy independent term which we identify as the diffractive cross section to be: σ(inelastic diffraction) = $3.41 - 1.54 = 1.87 \pm 0.16$ mb. The total inclusive differential cross section is given by $d\sigma/dM^2 = (15.7 \pm 1.1)/s + (3.8 \pm 0.3)/M^4$ mb/GeV^2.

An independent upper limit on the magnitude of a contribution to $d\sigma/dM^2$ of the form c/M^2 (such as due to a triple Pomeron coupling)[5] can be obtained from the small change of the inclusive cross section over a large energy range. The integral of c/M^2 from any fixed value of M^2 to any fraction of s varies with s as const. + ln(s).

Using values for the inclusive cross section integrated up to $M^2 = 0.1s$, i.e., $\sigma(s = 260\ GeV^2) = 3.4 \pm 0.2$ mb from our results[1] and $\sigma(s = 1464\ GeV^2) = 4.11 \pm 0.1$ mb from ISR[2] we obtain $1.73 \times c = .71 \pm .22$ or $c = .41 \pm .13$ mb. Lower limits can be obtained by fitting all data points. This of course is only an upper limit since the small observed energy dependence of the cross section could come in part or all from the scaling term.

We wish to congratulate here the whole Fermilab Accelerator staff for their successful operation of the accelerator at 500 GeV, which made this experiment possible. We acknowledge the help of the Internal Target Area staff and in particular we thank T. Nash for his help and encouragement. We also thank J. F. Brolley of Los Alamos Scientific Laboratory for use of a de Laval nozzle.

References

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[6]For a detailed description of the real time analysis see the second paper of Ref. 1 and references therein.

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Figure Captions

Fig. 1. The M^2 dependence of the inelastic differential cross section for 6 values of t at s = 940 GeV^2. The solid lines are fits (see text).

Fig. 2. The t dependence of the inelastic differential cross for $M^2 > 60$ GeV^2. The solid line is an exponential fit to the data (see text).

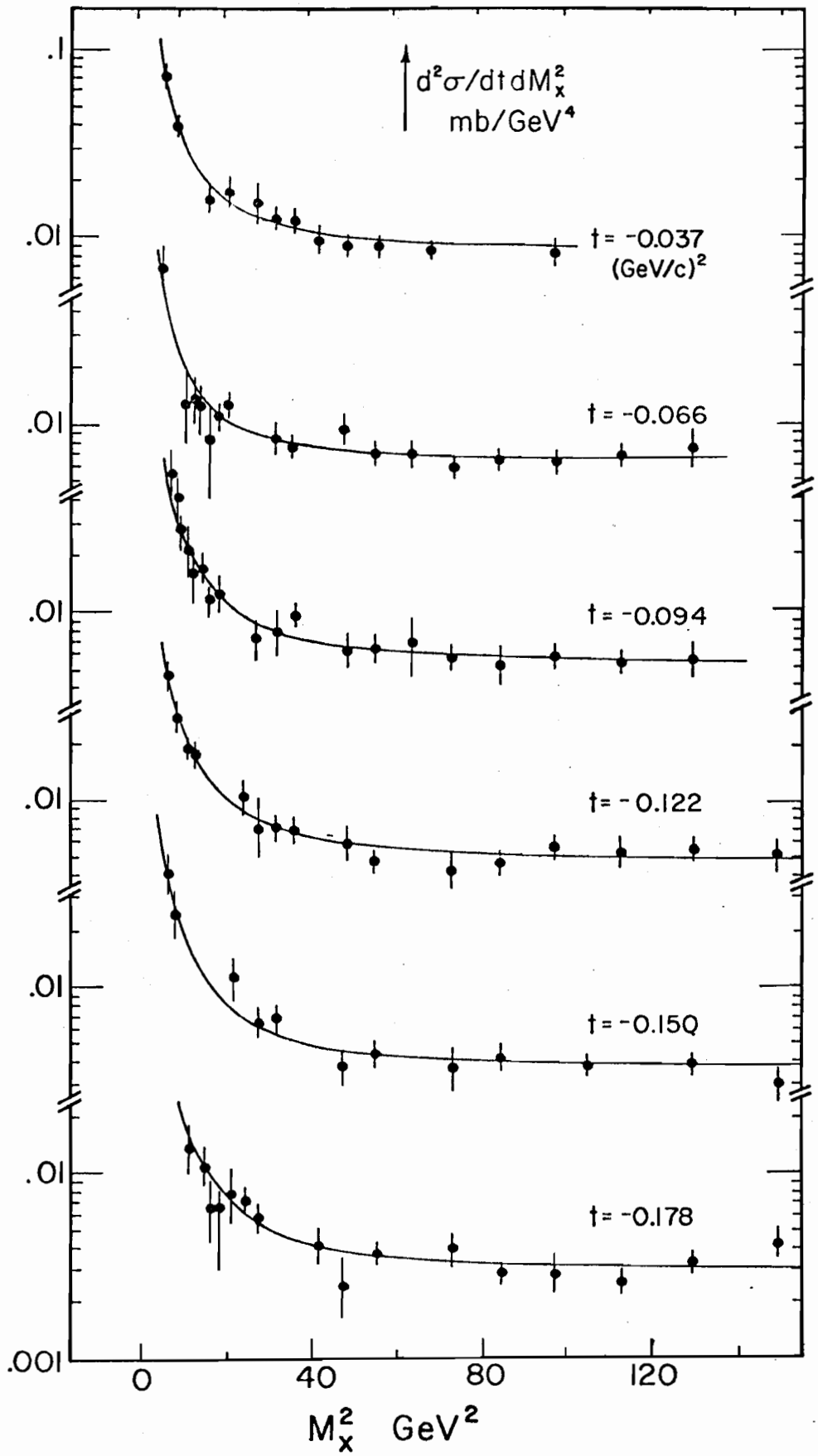
$d^2\sigma/dt\,dM_x^2$
mb/GeV^4
.1
.01
.01
.01
.01
.01
.001
t = -0.037
(GeV/c)^2
t = -0.066
t = -0.094
t = -0.122
t = -0.150
t = -0.178
0
40
80
120
M_x^2 GeV^2

Fig. 1

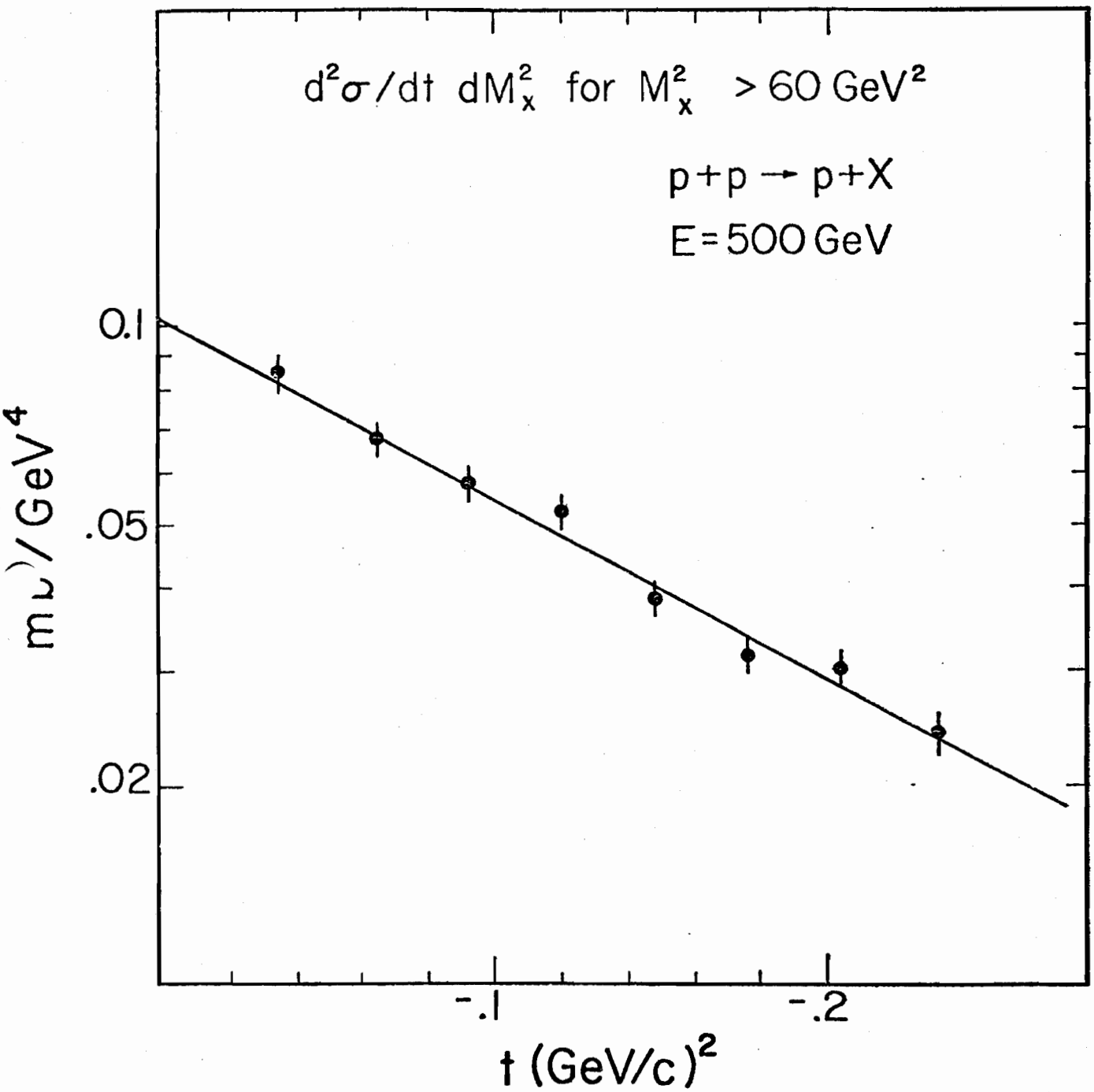
$d^2\sigma/dt\ dM_x^2$ for $M_x^2 > 60\ GeV^2$
p+p → p+X
E=500 GeV
0.1
.05
.02
mb/GeV^4
-.1
-.2
t (GeV/c)^2

Fig. 2