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Invariant Cross Sections for p + n → p + X Between 50 and 400 GeV*

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ABSTRACT

We have measured the inclusive cross sections for the reactions $p + p \rightarrow p + X$ and $p + d \rightarrow p + X$ in the region $0.14 < |t| < 0.38$ GeV^2, $100 < s < 750$ GeV^2 and $0.80 < x < 0.93$ using the acceleration ramp and hydrogen (deuterium) jet target at NAL. These measurements are combined to obtain invariant cross sections for $p + n \rightarrow p + X$.

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In a recent experiment we measured the inclusive cross sections for the reactions

$$p + p \rightarrow p + X \qquad (1)$$

$$p + d \rightarrow p + X \qquad (1 + 2 \rightarrow 3 + X) \qquad (2)$$

using the hydrogen (deuterium) jet target in the NAL main ring. The results of the $p + p \rightarrow p + X$ measurements were reported earlier[1]. In this letter we present cross sections for $p + d \rightarrow p + X$ and combine the two sets of measurements to obtain invariant cross sections for

$$p + n \rightarrow p + X \qquad (3)$$

We measure only slow proton recoils in the laboratory system, that is, in the "target fragmentation" region. The invariants we use are those of single nucleon scattering (see Ref. 1), except when discussing pd elastic scattering where

$$s_{el} = m_d^2 + m_p^2 + 2m_d E_1 \qquad (4)$$

$$t_{el} = m_d^2 + m_p^2 - 2m_d E_3 \qquad (5)$$

We define $x = 1-M^2/s$, where M is the mass of X and s is the center of mass energy squared.

The recoil proton was detected in a spectrometer consisting of a series of scintillation counters.[1] For each detected particle the time of flight was measured between two of these counters (186 cm apart) and the pulse height was measured in a long (20 cm) scintillation counter. This information was digitized and recorded on magnetic tape for analysis on an off-line computer.

Our pd inclusive cross sections were normalized to elastic pd cross sections. Recoil deuterons were detected in a small (1 cm^2) solid state detector (elastic monitor) at 85.5° from the beam direction. The luminosity was then determined from a knowledge of the differential cross section for pd elastic scattering at that angle.

The pd elastic differential cross-section is parameterized as

$$\frac{d\sigma(s,t)}{dt} = \frac{\sigma^2_{tot}(s)(1+\alpha^2)e^{bt+ct^2}}{16\ \pi\ h^2c^2} \qquad (6)$$

We use the Serpukhov[2] parameterizations of b, c, and α. For the total cross section we use Serpukhov data[3] and preliminary data from the BNL-NAL-Rockefeller collaboration[4].

The $p + d \rightarrow p + X$ data were taken with the same experimental arrangement as the $p + p \rightarrow p + X$ data, the only difference being the gas used in the jet target. Thus the relative normalization between the two sets of data depends only on the accuracy to which the pp and pd elastic differential cross sections are known.

Since the various momentum transfer intervals of our $p + d \rightarrow p + X$ data are collected simultaneously and the different points in x are determined merely by rotating the apparatus relative to the beam, always keeping the elastic monitor fixed, the relative normalization among the data at a particular incident energy is constant. Thus the uncertainties in relative

normalization are determined solely from uncertainties in the calibration of the proton recoil energy and angle, losses out of the apparatus due to nuclear and multiple Coulomb scattering, and the statistical fluctuations in the elastic monitor. We estimate a systematic error of ±3% from the effects listed above. We estimate the error on the relative normalization between our two extreme energies to be ±5% and the uncertainty in the overall normalization of the pd data to be ±15%.

The $p + d \rightarrow p + X$ data are shown in Fig. 1. Only statistical errors with relative systematics added quadratically are displayed. These data are similar to the $p + p \rightarrow p + X$ data. There is a small s dependence and an exponential t dependence ($\sim e^{6t}$). There is a minimum in the x distribution at about $x = 0.87$ and the cross section is about twice that of the $p + p \rightarrow p + X$ data.

However, it should not be assumed that the $p + n \rightarrow p + X$ data is the same as the $p + p \rightarrow p + X$ data from this similarity. The measured shapes of the pd inclusive spectra in our kinematic region (x near 1, low $|t|$) are determined to a large extent by the Fermi motion of the nucleons. Rescattering of the recoil particle off the spectator nucleon in the deuteron also plays a significant role.

To extract the $p + n \rightarrow p + X$ spectra we assume the impulse approximation. In this approximation the proton and neutron in the deuteron are considered as independent particles in close proximity. The closeness of the nucleons gives rise to a shadowing of one by the other, effectively lowering the luminosity of both relative to an equal number of free particles. This shadowing can be approximated by $\sigma_{pd} = \sigma_{pp} + \sigma_{pn} - \delta$ where $\delta = \frac{\sigma_{pn}\sigma_{pp}}{4\pi\langle r^2\rangle}$

with $\langle r^2 \rangle$ = 31 mb. This is approximately the cross section deficit of Glauber Theory [5] and amounts to a decrease of 5-6% in the effective pd cross section over our energy range.

The only effect of the deuteron potential in the impulse approximation is to give the nucleons a center of mass momentum or Fermi motion. This is approximated by the Hulthen distribution [6]

$$\text{prob}(p) = \frac{Ap^2}{(p^2+a^2)^2(p^2+b^2)^2} \qquad (7)$$

with a = 0.0458 GeV, b = 0.285 GeV, and A = 0.0055 GeV^3.

Fermi motion, experimental resolution, and pp elastic scattering differential cross sections[7] were used in a Monte Carlo program to simulate the pp elastic spectra as seen by our spectrometer. These spectra are approximately gaussian around the peak value of x which in our definition of x occurs at $x = 1-m_p^2/s$.

The $p + p \rightarrow p + X$ spectra smeared by Fermi motion were estimated by another Monte Carlo program using a composite input of the available data.[1,8,9,10]

For both the pp elastic and inelastic cross sections mentioned above we use the forms for "free" protons but modified by the deuteron form factor in order to exclude interactions which result in a deuteron in the final state which is not detected, i.e., for the pp differential cross sections we use $d\sigma/dt = d\sigma/dt_{free}\ [1 - S^2(t)]$ where $S^2(t)$ is the deuteron form factor.

An additional feature of the Monte Carlo programs was the inclusion of an estimate of the rescattering of the recoil protons by the spectator neutron which has the effect of spreading the x distributions for those protons which interact. For this, we

assume that the neutron on average sits at a r_{rms} of $\sqrt{31.\ mb}$ and that the reaction is the same as for free np scattering. The probability for an interaction is simply $\sigma_{pn}(t)/4\pi\langle r^2\rangle$. Low energy np total cross section measurements were used for this purpose. Also, the scattering angle was weighted by low energy np differential cross section measurements.[11]

We have included no double scattering correction (where the incident proton or one of its fragments interacts with both particles in the deuteron). While we expect this to be small, we have found no reliable way of estimating it.

Summarizing, our final $p + n \rightarrow p + X$ cross sections were obtained in the following manner: 1) Our $p + d \rightarrow p + X$ cross sections were multiplied by 1.05 to correct for the shadowing effect. 2) From the resulting cross sections we subtracted the $p + p \rightarrow p + p$ elastic and $p + p \rightarrow p + X$ cross sections both of which where Fermi smeared, corrected for coherent pd scattering (by including the deuteron form factor) and corrected for rescattering off the spectator neutron.

A typical spectrum and the distributions from which it was derived is shown in Fig. 2. The final $p + n \rightarrow p + X$ spectra are plotted in Figs. 3-6. Only errors for s=752 GeV^2 are shown, the other energies having similar errors at the same x. The errors are quite large because the systematics involved in the subtraction proceedure are rather large. Also, the final data are often much smaller than the original $p + d \rightarrow p + X$ spectra.

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In conclusion, we have measured the $p + d \rightarrow p + X$ inclusive spectra over an energy range $100 < s < 750$ GeV^2 and extracted an estimate of the $p + n \rightarrow p + X$ spectra from these assuming the impulse approximation and free np scattering of the recoil protons. The $p + n \rightarrow p + X$ spectra decrease rapidly with x and t and are constant in s within errors.

We are grateful to the USSR-USA collaboration and the members of the Internal Target Laboratory for providing the jet target facility and the elastic monitor. We also wish to thank D. Jovanovich, E. Malamud, J. Sanford and the Accelerator Section for their help and cooperation. The advice and contributions of B. Maglich are warmly acknowledged.

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Figure Captions

Fig. 1 x distributions of our pd→pX data over our 4 t bins and 4 s ranges. There is an absolute normalization uncertainty of ±15%. The errors shown are ±3% relative systematics and statistical errors added quadratically.

Fig. 2 Sample subtraction proceedure for s = 503 GeV^2 at $-t = 0.25$ GeV^2. The smeared pp spectra are subtracted from the luminoisity corrected pd spectrum to get the pn→pX spectrum.

Fig. 3-6 The pn→pX spectra are shown for each t bin separately for all s. Only errors for s = 752 GeV^2 are shown, other energies at the same x have similar errors.

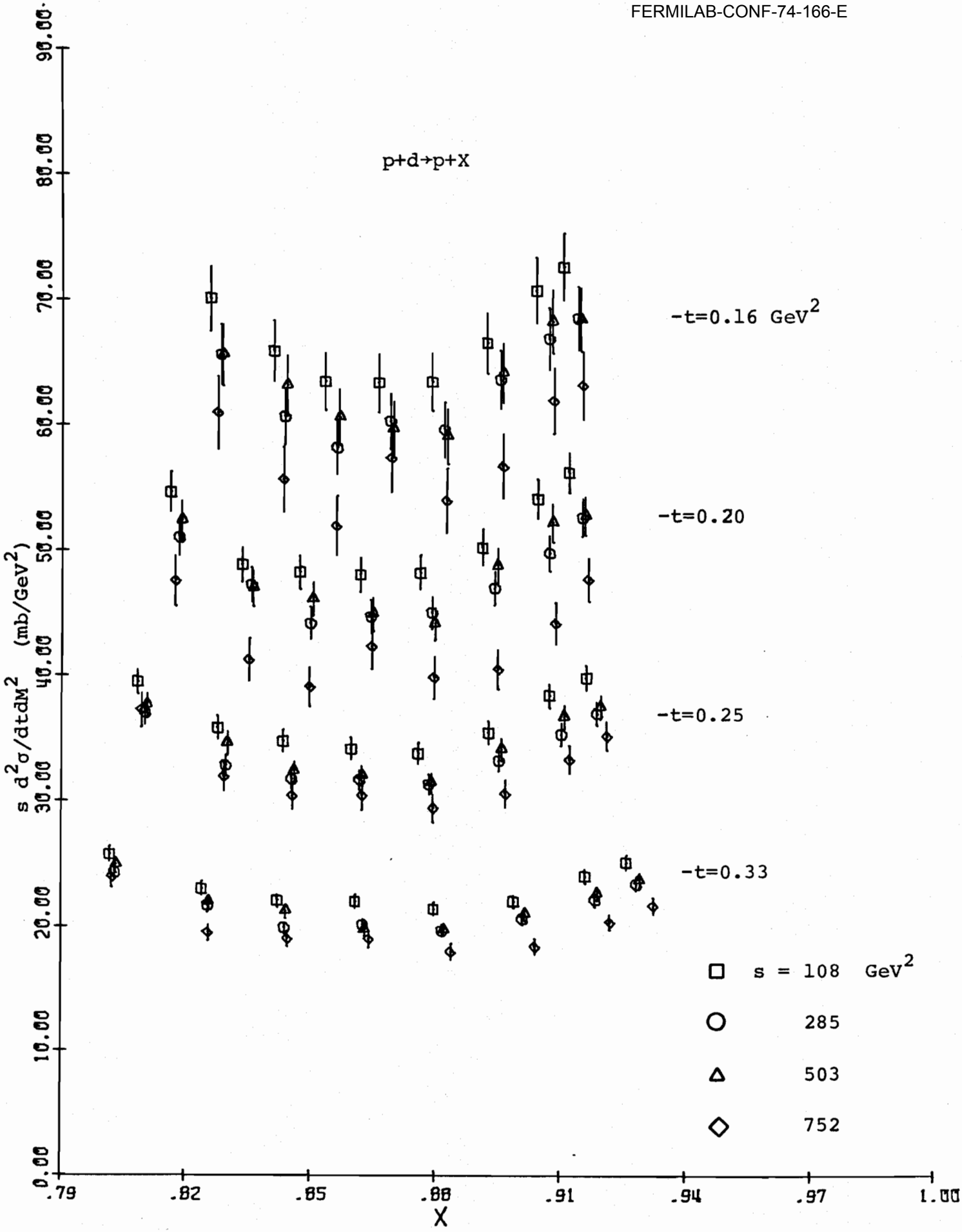
p+d→p+X
-t=0.16 GeV^2
-t=0.20
-t=0.25
-t=0.33
s = 108 GeV^2
285
503
752
s d$^2\sigma$/dtdM^2 (mb/GeV^2)
X
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
.79
.82
.85
.88
.91
.94
.97
1.00

Fig. 1

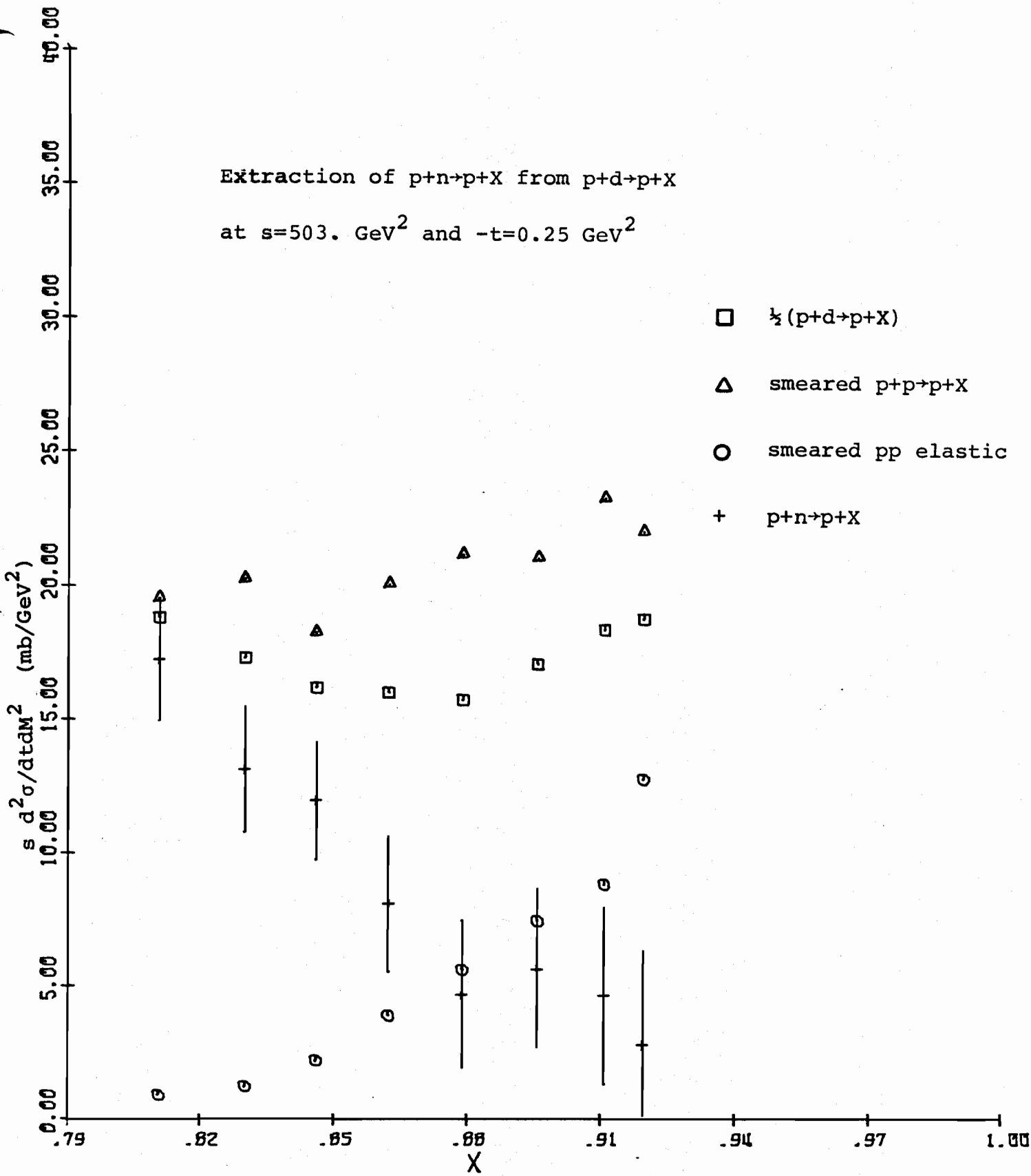
Extraction of p+n→p+X from p+d→p+X
at s=503. GeV^2 and -t=0.25 GeV^2
½(p+d→p+X)
smeared p+p→p+X
smeared pp elastic
p+n→p+X
s d^{2}σ/dtdM^2 (mb/GeV^2)
X
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
.79
.82
.85
.88
.91
.94
.97
1.00

Fig. 2

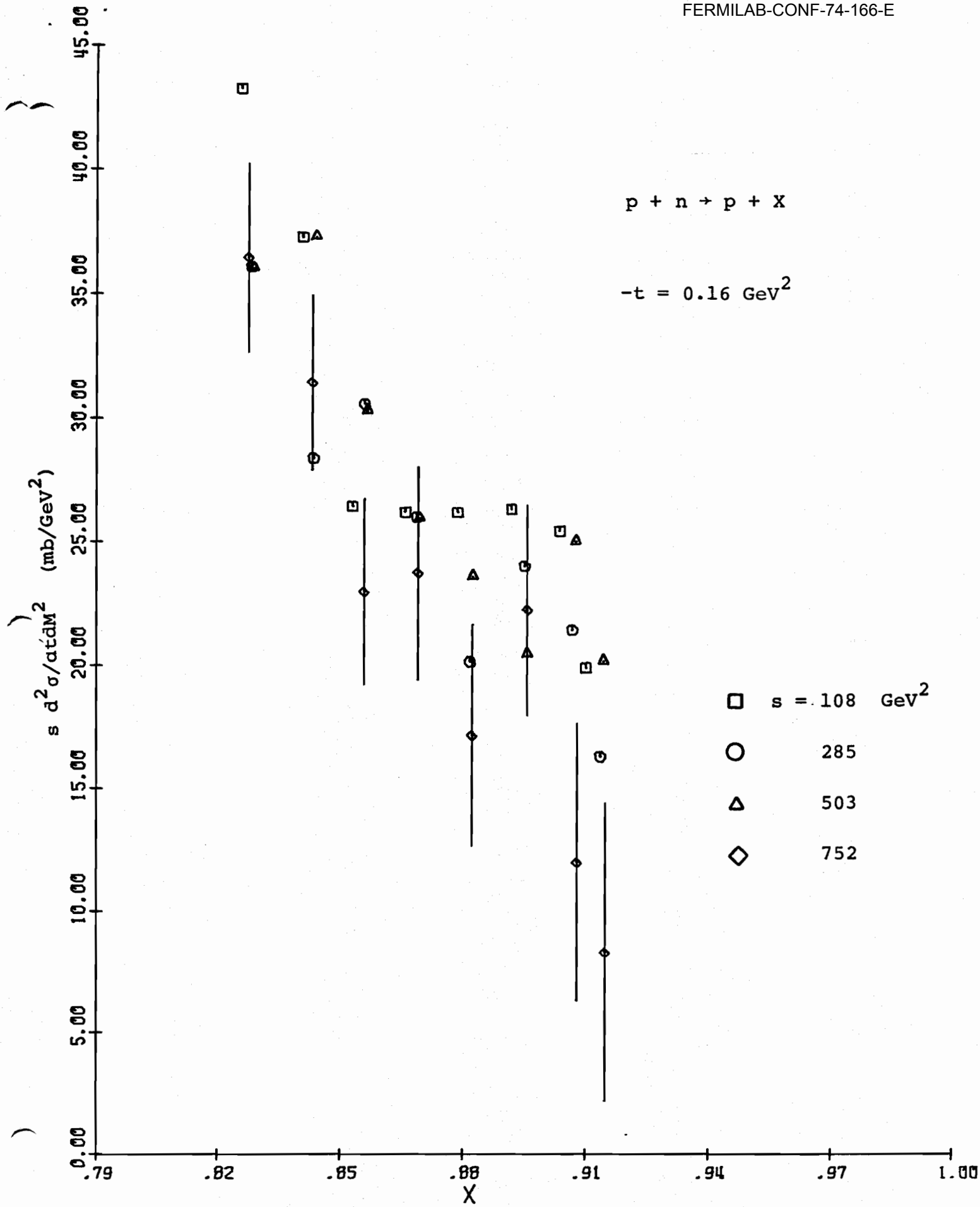
p + n → p + X
-t = 0.16 GeV^2
s = 108 GeV^2
285
503
752
s d$^2\sigma$/dtdM^2 (mb/GeV^2)
X
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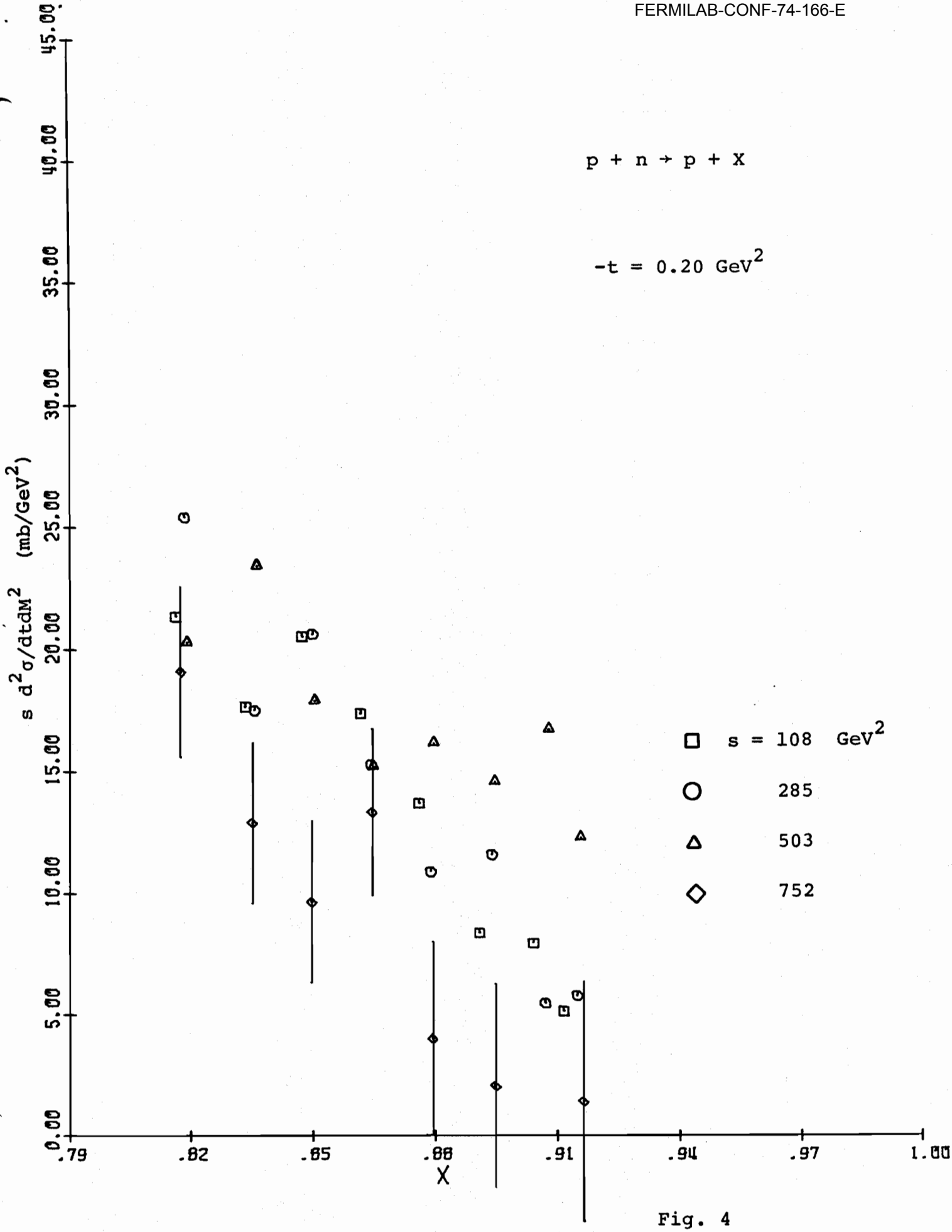
Fig. 3


p + n → p + X
-t = 0.20 GeV²
s d²σ/dtdM² (mb/GeV²)
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s = 108 GeV²
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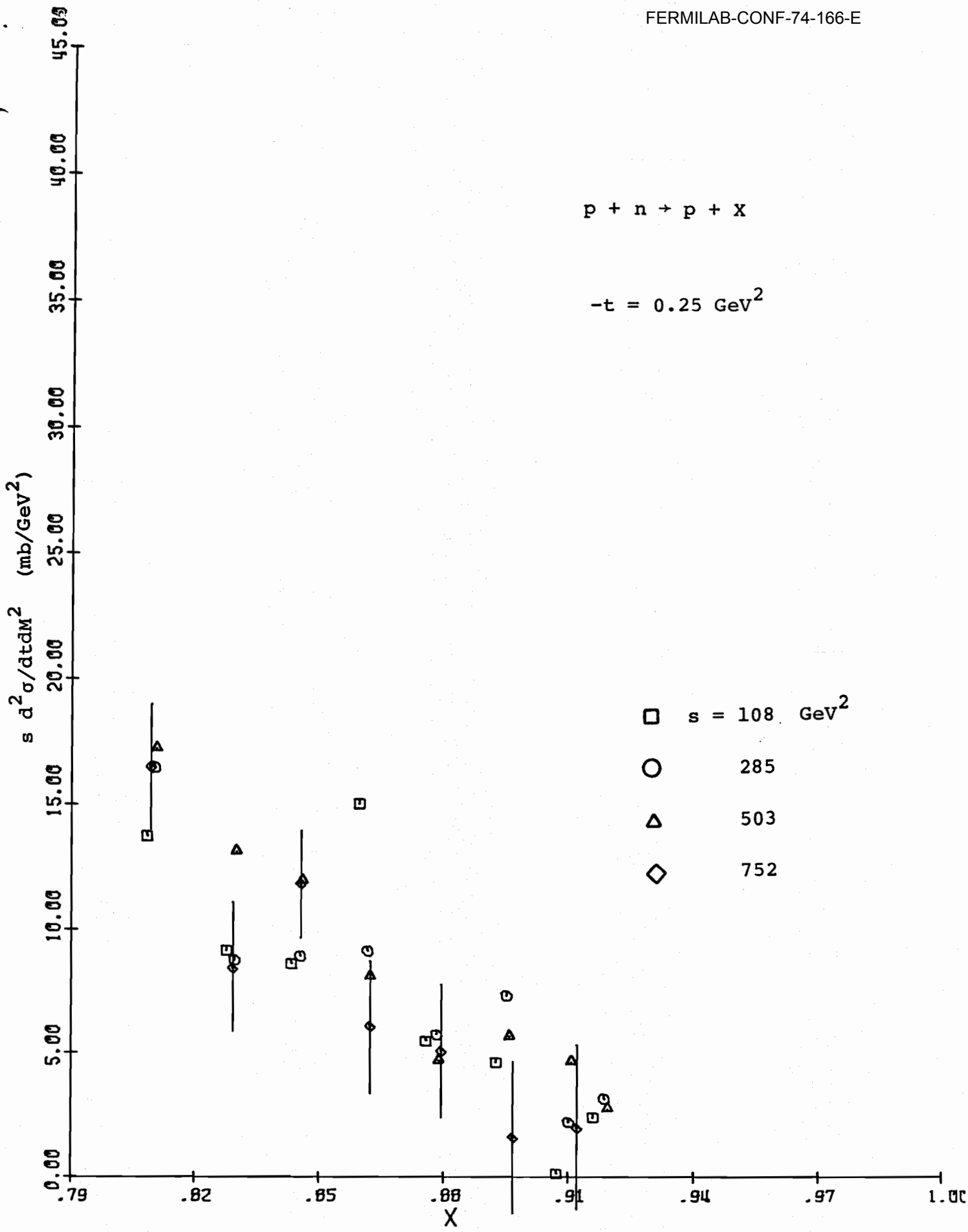
Fig. 4


p + n → p + X
-t = 0.25 GeV²
s = 108 GeV²
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s d²σ/dtdM² (mb/GeV²)
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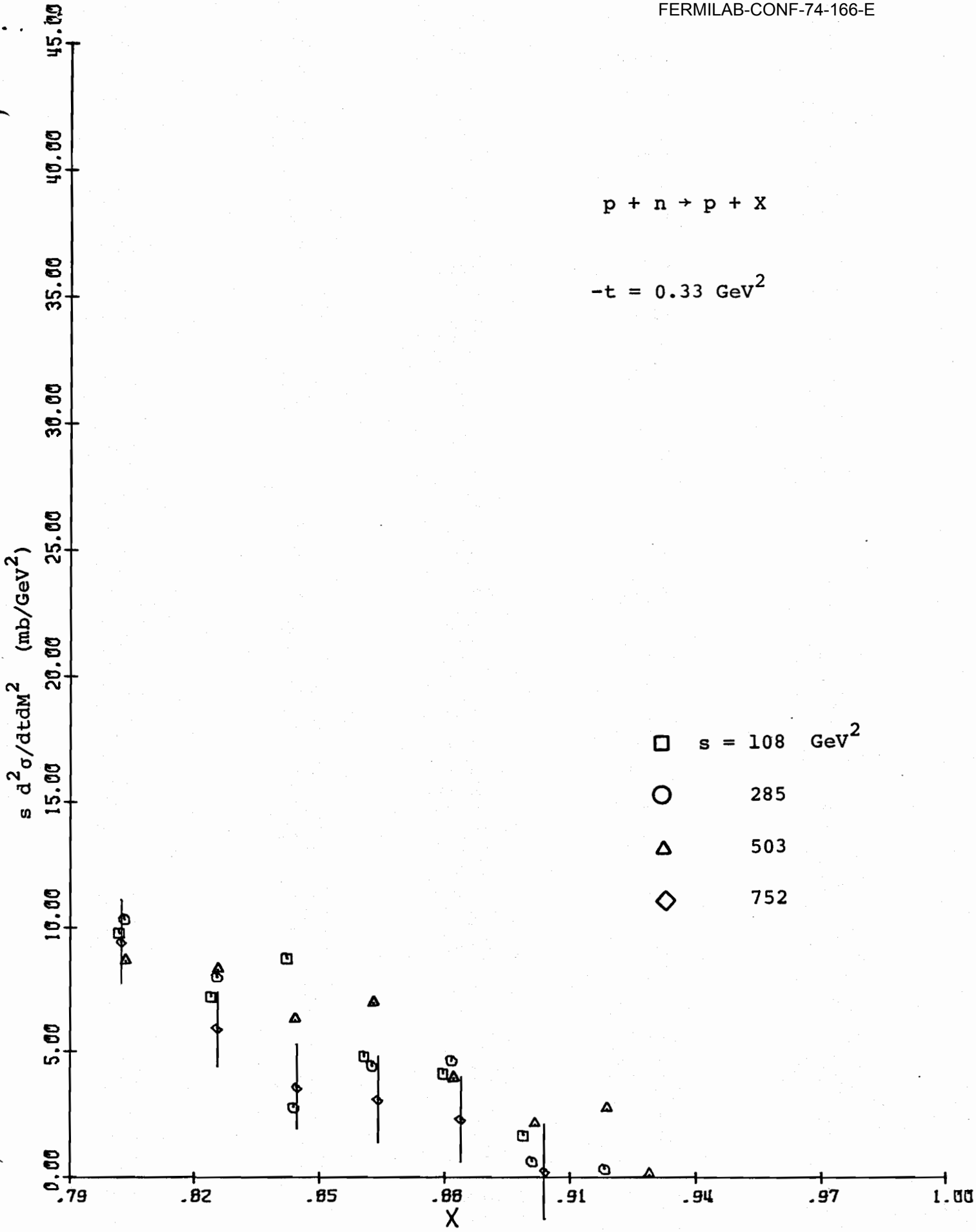
Fig. 5


p + n → p + X
-t = 0.33 GeV^2
s = 108 GeV^2
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752
s d^{2}σ/dtdM^2 (mb/GeV^2)
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Fig. 6