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Proton-Deuteron Elastic Scattering from 25 to 210 GeV/c*

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Measurements of the differential cross-section for proton deuteron elastic scattering are reported for incident proton momenta ranging from 25 to 210 GeV/c and for invariant four momentum transfers of $0.6 \leq |t| \leq 3.0$ $(GeV/c)^2$. The results are compared with the Glauber double scattering model.

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The study of high energy reactions in nuclei has received considerable attention in recent years both as a technique for studying the space-time development of high energy processes[1] and also as a method for measuring the interaction cross-sections of unstable particles[2]. Of the various reactions and nuclear targets considered, high energy elastic proton deuterium scattering has the unique advantage of involving well understood single nucleon processes in a system where the nuclear physics can be reliably calculated. A multiple scattering theory for scattering from deuterium has been developed by Glauber[3]. In this picture elastic scattering with invariant four momentum transfers, t, beyond about 0.6 $(GeV/c)^2$, is dominated by double scattering; i.e. by successive scatters from both nucleons in the deuteron. More recently the importance of multiple exchanges or cuts in high energy elementary particle reactions has been noted[4]. The double scattering process in deuterium could serve as a simple example where techniques for calculating these multiple exchange processes can be tested.

In an experiment performed at the Internal Target Area of the Fermi National Accelerator Laboratory (FNAL), we have measured the differential cross-section for proton deuteron elastic scattering by detecting recoil deuterons from an internal deuterium gas jet target. Data were taken for incident momenta, p_o, ranging from 25 to 210 GeV/c and for invariant four momentum transfers of $0.6 \leq |t| \leq 3.0$ $(GeV/c)^2$.

We identified the elastic scattering process by accurately measuring θ, the recoil angle relative to the incident beam direction, and the recoil momentum, p_r. From these, the mass, M_x, of the undetected forward system could be inferred via the relation

$$M_x^2 = m_p^2 + 2p_o \quad (p_r \cos\theta - T_r/\beta^*) \quad . \qquad (1)$$

Here T_r is the kinetic energy of the recoil particle and $\beta^*= p_o/(E_o+m_p)$ is the velocity of the cm system in the laboratory. Equation 1 illustrates that in order to separate elastic events ($M_x=m_p$) from those events where X corresponds to a low mass inelastic state, good resolution is needed in θ and p_r, particularly at large values of p_o.

The recoil deuterons were detected in a large angle recoil spectrometer shown in Fig. 1. This device consists of a superconducting quadrupole doublet, situated near the gas jet target, set to focus parallel rays from the target to a point at a plane which is coincident with the exit window of an extension to the accelerator vacuum chamber. A Multi Wire Proportional Chamber (MWPC) situated at the exit point registers this position and is used to infer the scattering angle at the target with essentially no error introduced by multiple scattering. The precision of the recoil angle determination is estimated to be $\pm$ 0.5 mrad. The recoil momentum is determined by measuring the bend angle in a superconducting dipole as shown in Fig. 1. MWPC's before and after the magnet determine the incident and exit trajectories. In order to minimize multiple scattering MWPC's 3 and 4, directly in front and back of the magnet are immersed in a helium drift volume, separated from the helium gas by 6 micron Acclar windows. This yielded a precision on the recoil momentum of $\sim \pm 0.002\, p_r$, enabling the clear separation of the elastic and inelastic reactions. A solid state detector telescope situated at θ=84.5° monitored small t elastic scattering and was used to infer the beam-gas jet target luminosity in a manner analogous to that described in Ref. 5.

Data were taken at different t values by varying the angle and central momentum setting of the spectrometer. The incident momentum was varied by pulsing the gas jet during different portions of the acceleration cycle. The spectrometer was triggered by a four fold coincidence of the trigger counters T_1 through T_4 (see Fig. 1). Deuterons were identified by their time of flight between counters T_1 and T_4.

The quadrupole optics enabled the reconstruction of the target position with a precision of $\pm$ 0.4 cm. Recoils were required to originate within $\pm$ 2 cm of the target center (the gas jet profile has been measured to be Gaussian with a σ of 0.3 cm). The trajectory information before and after the dipole allowed for one constraint to be imposed on the momentum determination. Furthermore, only those events in which the front and rear tracks intersected (to within 0.5 cm) at the magnet midplane were accepted. The momentum determination was subsequently used to correct for chromatic aberrations in the recoil angle determination. In this way we obtained a clean sample of events with good efficiency.

Each event was subjected to an elastic hypothesis, i.e., the measured recoil momentum was compared to that predicted from the production angle and elastic kinematics. A typical distribution in the difference between the measured and inferred momentum, for an incident momentum of 120 GeV/c, is shown in Fig. 2. A clean peak is evident near $\Delta p_r/p_r=0.0$, with a broad distribution of counts for $\Delta p_r/p_r < 0.0$, corresponding to inelastic processes. To determine the number of elastic counts, a fit was made to this distribution with a Gaussian for the elastic peak and a smooth polynomial (together with resonance shapes centered at $M_x = 1.52$ and 1.69) for the background. This fit is shown in Fig. 2 as the smooth curve. The number of elastic counts were then normalized using the solid state detector monitor, correcting for spectrometer and reconstruction efficiencies and also the spectrometer acceptance.

The efficiency correction, which included the effects of the analysis cuts as well as the effect of event loss due to multiple track confusion was determined directly from the data to be 94 ± 2 percent. The acceptance of the spectrometer was computed by generating Monte Carlo events, allowing them to multiple scatter in the spectrometer elements and subjecting them to the same analysis procedure. The estimated uncertainties to these corrections are ±5 percent of the cross-section and have been combined in quadrature with the statistical errors. The overall normalization uncertainty is estimated to be ±10 percent. The normalization was checked by taking pp elastic scattering data in the region ($0.30 \leq |t| < 0.70$ $(GeV/c)^2$), and processing it in the same manner as the pd data. The resulting pp elastic cross sections agree within errors (typically ± 5%) with the results of Ayres et al.[6]

Differential cross-sections are shown as a function of t for p_o=25, and 120 GeV/c in Fig. 3. Included in this figure are the results at 9.6 GeV/c of Bradamante et al.[7], those at 24 GeV/c of Allaby et al.[8], and the ISR results at a laboratory equivalent momentum of 1037 GeV/c of Goggi et al.[9] Our 25 GeV/c cross sections are significantly lower than those of Allaby et al.[7] The 120 GeV/c cross sections are within errors equal to the high energy ISR results.

In the Glauber model these differential cross sections (for $|t| \geq 0.6$ $(GeV/c)^2$) are given by[7]

$$\frac{d\sigma}{dt}(t) = \frac{I_G^2}{\pi}\left[\frac{d\sigma_{pp}}{dt}(t/4)\right]\left[\frac{d\sigma_{np}}{dt}(t/4)\right] \qquad (2)$$

where the Glauber integral I_G is defined as

$$I_G = \frac{1}{2}\int_0^\infty S(t)\, e^{b_{pp}t/2}\, e^{b_{pn}t/2}\, dt \,. \qquad (3)$$

Here b_{pp} and b_{pn} are the elastic pp and pn slope parameters and S(t) is the deuteron scalar form factor. Quadrupole contributions to Eq. (3) are expected to be small and have been neglected. Assuming that the pp and pn differential cross-sections are the same, we have evaluated I_G, over the range of values for b_{pp} reported in Ref. 6. The value of the integral is found to be constant (to within ±3 percent) at a value of 0.028 mb^{-1} over the energy range covered by this experiment. The resulting predictions using the Regge fit to the pp cross section reported in Ref. 6, are also plotted in Fig. 3. Note that the data generally lie significantly below the model and have a slower fall off in t.

In Fig. 4 $d\sigma/dt$ is plotted vs the incident momentum. The data are relatively constant with momentum for $|t|$ values below 1.0 $(GeV/c)^2$. At $t=-1.2$ and above there is an abrupt drop at low energy which flattens out at the higher energies. This is reflected in the low energy differential cross-section (Fig. 3) as a shoulder at about $t=-1.3$ $(GeV/c)^2$. Included in Fig. 4 are smooth curves corresponding to the predictions of the Glauber model (Eq. (2)). For all t values, at energies above 50 GeV/c, the data are consistently about 40 percent below the Glauber model prediction.

Because the model depends upon the square of the pp differential cross section, predictions of the model are correspondingly quite sensitive to uncertainties in pp values. The experimental situation regarding pp elastic scattering in this t range is well summarized in Ref. 6. They find rather good consistency both with other experiments and also with the optical theorem and estimate the precision of their overall normalization to be 3%. The formula used was a good fit to their data which had typically errors of 3 to 4%. The overall uncertainty due to the experimental input into the Glauber prediction (1970) is thus expected to be about 10%.

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Figure Captions

1. A plan view of the Large Angle Recoil Spectrometer at the FNAL Internal Target Area.

2. The observed $\Delta p_r/p_r$ spectrum at $t=-1.3$ $(GeV/c)^2$, $P_{inc}=120$ GeV/c.

3. Proton-deuteron differential elastic cross sections $d\sigma/dt$, plotted vs. t. The curves are Glauber model predictions at 25 GeV (upper) and 120 GeV (lower).

4. Proton-deuteron differential elastic cross sections $d\sigma/dt$ plotted vs. the incident momentum. The curves are Glauber predictions. Several points at $|t| > 1.4$ $(GeV/c)^2$ are interpolated in t from nearby measured points.

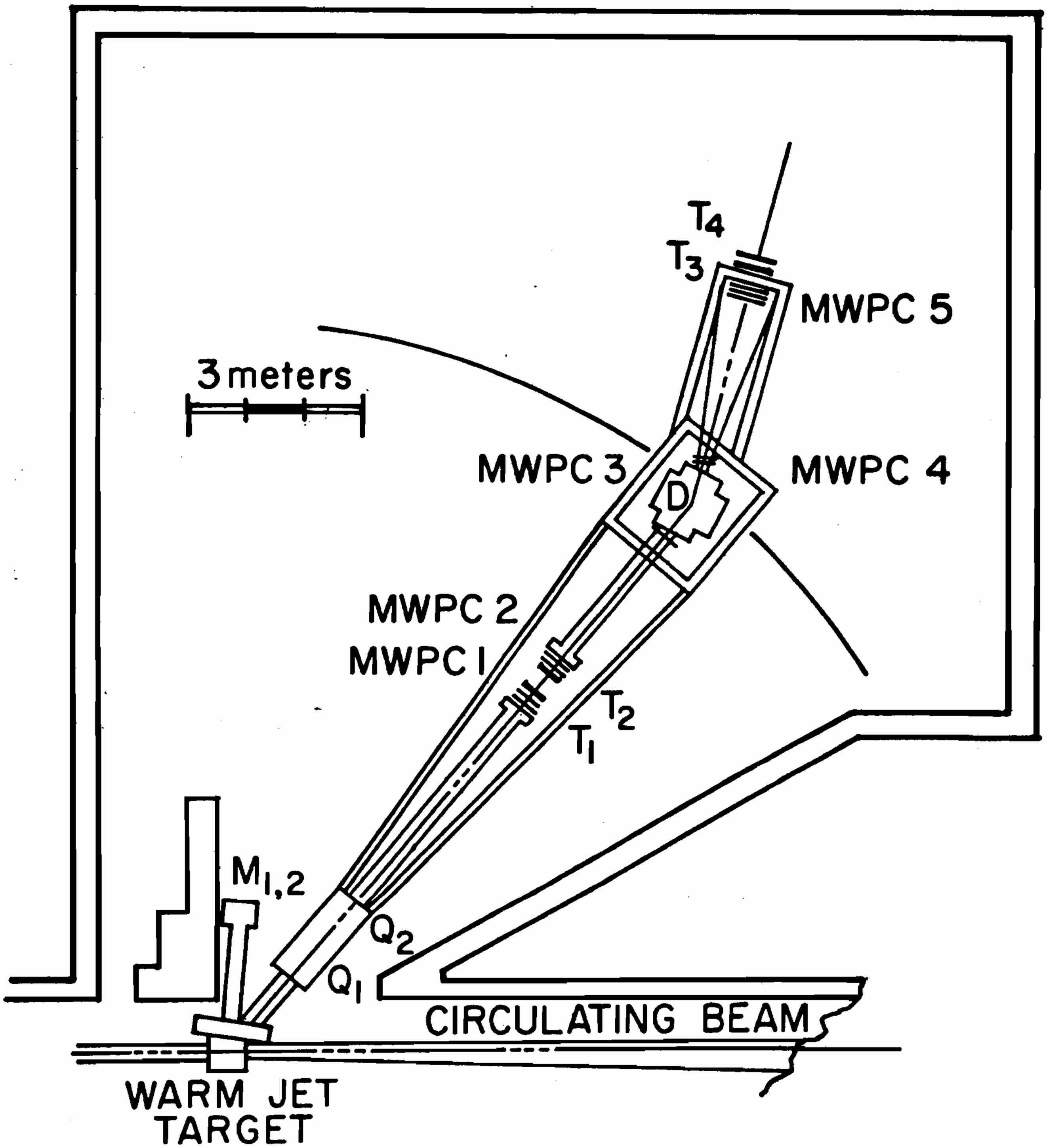

T4
T3
MWPC 5
3 meters
MWPC 3
D
MWPC 4
MWPC 2
MWPC 1
T2
T1
M1,2
Q2
Q1
CIRCULATING BEAM
WARM JET
TARGET

Figure 1

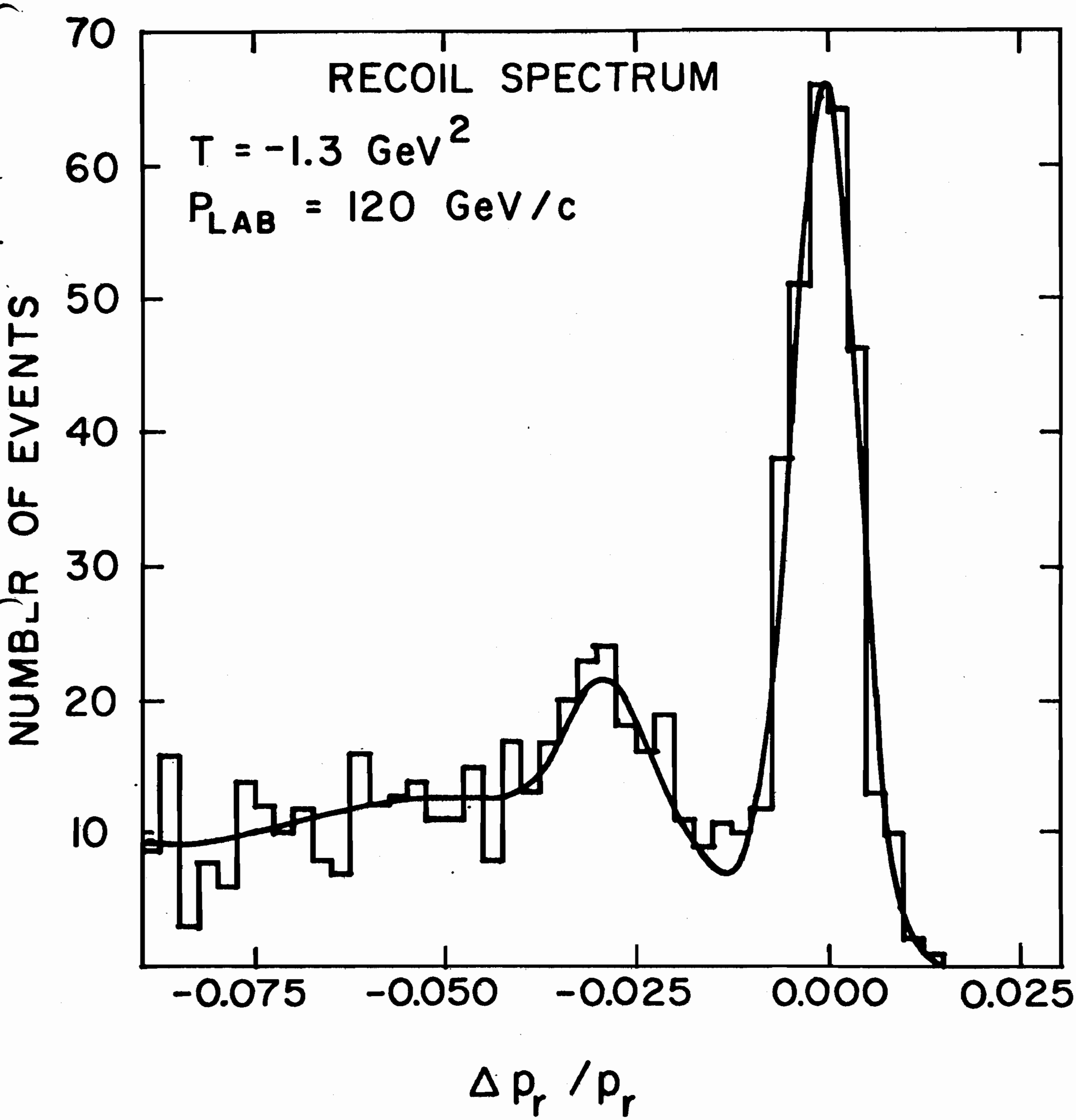
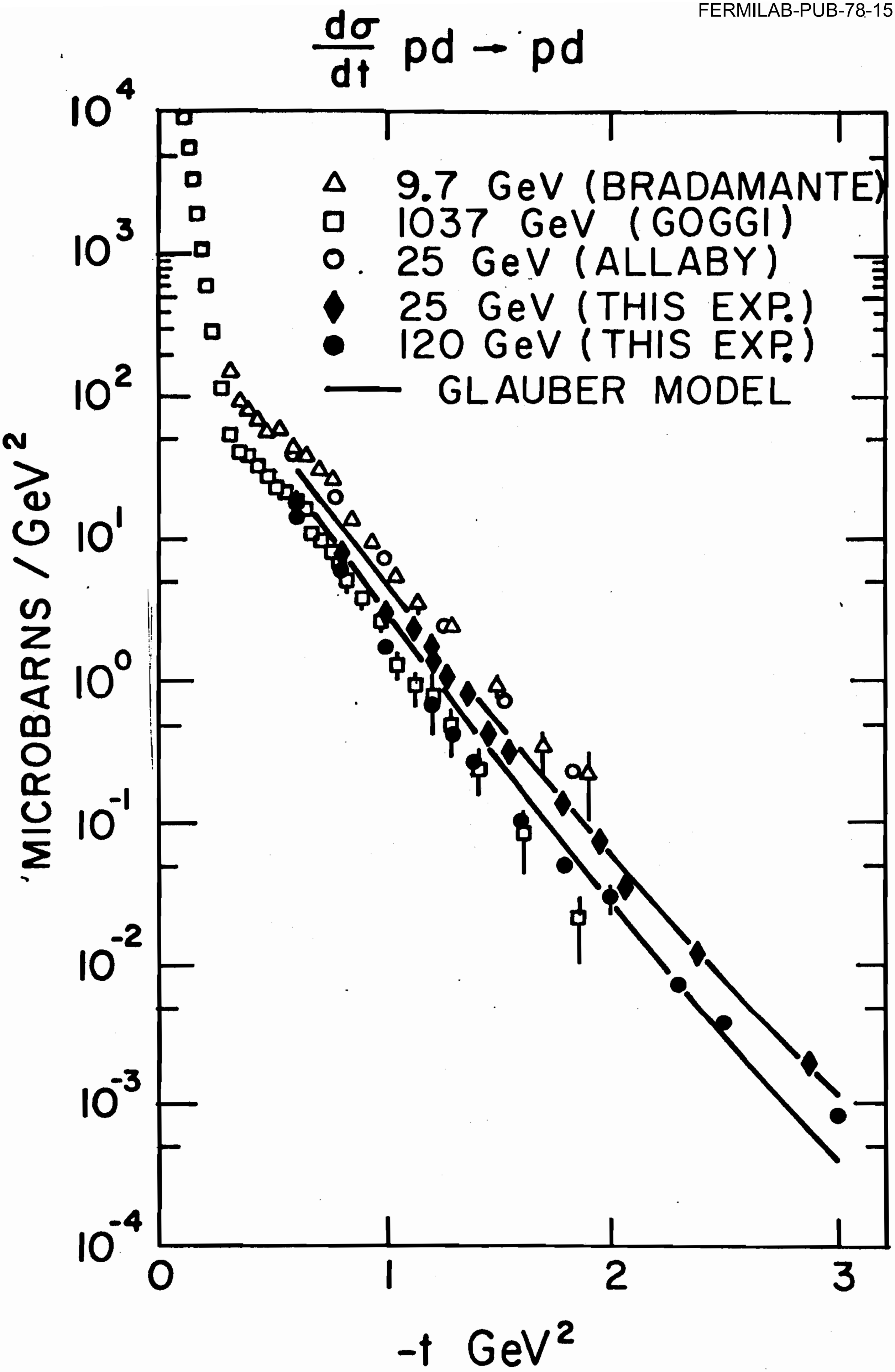
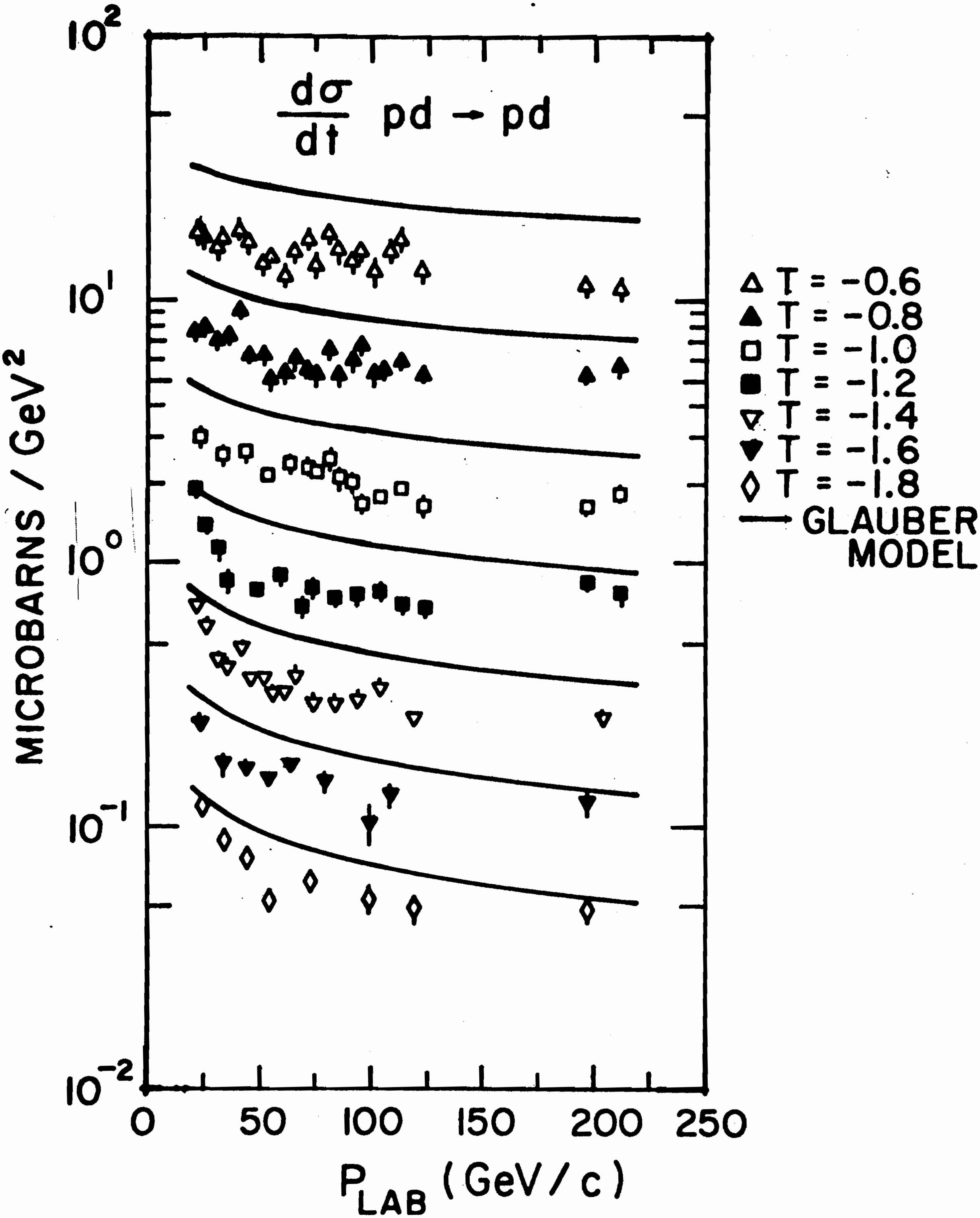

RECOIL SPECTRUM
T = -1.3 GeV2
PLAB = 120 GeV/c
NUMBER OF EVENTS
70
60
50
40
30
20
10
-0.075
-0.050
-0.025
0.000
0.025
Δ pr / pr

Figure 2



$\frac{d\sigma}{dt}$ pd → pd
9.7 GeV (BRADAMANTE)
1037 GeV (GOGGI)
25 GeV (ALLABY)
25 GeV (THIS EXP.)
120 GeV (THIS EXP.)
GLAUBER MODEL
MICROBARNS / GeV²
-t GeV²

Figure 3



dσ/dt pd → pd
MICROBARNS / GeV²
10²
10¹
10⁰
10⁻¹
10⁻²
0
50
100
150
200
250
P_LAB (GeV/c)
T = -0.6
T = -0.8
T = -1.0
T = -1.2
T = -1.4
T = -1.6
T = -1.8
GLAUBER MODEL

Figure 4