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STUDY OF THE INCLUSIVE REACTION $p + p \rightarrow p + X$ BETWEEN 35 AND 200 GeV/c USING THE INTERNAL H_2 JET TARGET* AT NAL†

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ABSTRACT

We have measured the relative energy dependence of the invariant cross section for the inclusive reaction $p + p \rightarrow p + X$ for $s/M^2 = 5.7$ and 11 at $t = -0.33$ GeV^2 and $s/M^2 = 5.7$ and 13 at $t = -0.44$ GeV^2 using the acceleration ramp of the NAL machine from $p_{lab} = 35$ to 200 GeV/c. The data are compared with the triple Regge formula.

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We have measured the s and s/M^2 dependence of the invariant cross section for the single particle inclusive reaction

$$p + p \rightarrow p + X \qquad (1 + 2 \rightarrow 3 + X) \tag{1}$$

(X = anything) at the National Accelerator Laboratory using the acceleration ramp from p_{lab} = 35 to 200 GeV/c and the internal H_2 jet[1] target. Recoil protons from reaction (1) with $55^o < \theta_3 < 65^o$ in the laboratory exit the main accelerator beam pipe through a 3-mil titanium window and are detected in a counter-range telescope (Fig. 1). Two recoil momentum bites are selected simultaneously by means of three aluminum absorbers, the trigger logic being $C_1C_2C_3C_4C_5\bar{C}_6$ and $C_1C_2C_3C_4C_5C_6\bar{C}_7$. The protons of interest have $560 < p_3 < 660$ MeV/c and $660 < p_3 < 780$ MeV/c, $\beta \simeq 0.54$ and 0.60 and are 2.5 and 2.0 times minimum ionizing respectively. They are distinguished from pions of the same ranges by means of time-of-flight between counters C_1 and C_4 and pulse height in counters C_1 through C_5. The pion rates are monitored simultaneously with the proton rates for normalization purposes. A separate counter telescope at 45° in the laboratory measures the rate of fast charged particles from the target.

We describe the kinematics of reaction (1) by the three invariants s, t, and s/M^2 where M is the mass of X. We have

$$s = (p_1 + p_2)^2 \simeq 2mE_1 \tag{2a}$$

$$t = (p_2 - p_3)^2 = -2m(E_3 - m) \tag{2b}$$

$$M^2 = (p_1 + p_2 - p_3)^2 \simeq s[1 - (E_3 - p_3\cos\theta_3)/m] \tag{2c}$$

where m is the proton mass. Our data were collected at two spectrometer angles $\theta_3 = 55.6^\circ$ and 64.3° and two recoil momenta as defined earlier. Eqs. (2) imply that, for p_3 and θ_3 fixed, t is fixed and s/M^2 is nearly fixed for all s. The above angles together with the two recoil momentum bites define the values $s/M^2 = 5.7$ and 11 at $t = -0.33$ GeV^2 and $s/M^2 = 5.7$ and 13 at $t \doteq -0.44$ GeV^2 at which our data are taken. The variation of s/M^2 as p_1 goes from 35 to 200 GeV/c is 1% at $\theta_3 = 55.6^\circ$ and 4% at $\theta_3 = 64.3^\circ$.

The event rate in the spectrometer is given by

$$N = N_b N_t \frac{d^2\sigma}{d\Omega\, dp_3} \Delta\Omega \Delta p_3 \tag{3}$$

where N_b and N_t are the number of beam and target particles respectively and the product $N_b N_t$ represents the luminosity. The hydrogen jet target is essentially a vertical cylinder of approximately 5 mm diameter. It is pulsed for 200 ms twice during the 2 sec acceleration ramp of the machine. The hydrogen jet density is roughly 10^{-7} gm/cm^2 and may vary up to a factor of two over a period of a few hours. Above 30 GeV/c the circulating beam profile is an ellipse with approximate dimensions 2 x 3 mm in the vertical and radial directions respectively. The beam radius varies during the acceleration cycle so that in order to hit the jet at a particular energy the beam has to be steered onto the jet by applying a small perturbation to the main ring rf.

The mode of operation described above requires that the luminosity be monitored continuously during each run. As we have no absolute measurement of $N_b N_t$ we rely on two relative luminosity monitors to normalize runs taken at different angles and energies. At fixed energy but different spectrometer angles, we normalize the proton data by the counting rate in the separate counter telescope at 45° in the laboratory. At fixed spectrometer angle but different energies we normalize to the number of recoil pions from the reaction

$$p + p \rightarrow \pi^{\pm} + X. \tag{4}$$

The pions are monitored in the same spectrometer in which the proton rates from reaction (1) are measured. In this way we automatically take into account any possible variation in the spectrometer acceptance due to vertical and radial changes in the circulating beam position during acceleration. Pions from reaction (4) detected at 55.6° and 64.3° in the laboratory and stopped in the absorbers have $0.18 < p_\perp < 0.20$ GeV/c and $0.14 < |x| < 0.18$ where x is the Feynman variable.

Reaction (4) has been studied at sub NAL and ISR energies and there is evidence that in the above kinematic region the invariant cross section is independent of energy[2,3]. The pion rate therefore provides an energy independent monitor of the luminosity. In order to obtain an absolute normalization, we fit our data at $s/M^2 = 5.7$ with a function of the form $A + B/\sqrt{s}$ and extrapolate to the data of Allaby et al.[4] at $s = 46.8$ GeV^2.

The pulsed mode of operation of the hydrogen jet allows us to study "target in" and "target out" rates during the same acceleration cycle. Target out rates in the recoil spectrometer are less than 1% of the target in rates. Corrections for accidental vetoes introduced by counters C_6 and C_7 are also less than 1%.

In Fig. 2 we present our data from reaction (1) in terms of the invariant cross section $sd^2\sigma/dtdM^2$. For fixed recoil momentum p_3, this quantity is measured directly by our apparatus since we have

$$\frac{d^2\sigma}{d\Omega dp_3} = p_3{}^2 \frac{d^3\sigma}{d^3p_3} = \frac{1}{\pi}\frac{p_3{}^2}{E_3}\frac{sd^2\sigma}{dtdM^2} \quad . \tag{4}$$

The statistical errors on each point are less than 3%. We have added quadratically relative normalization errors which we estimate to be 4%. Our data establish the presence of an energy dependent component which makes a significant contribution to the invariant cross section up to the highest energies available. A fit of the form $A + B/\sqrt{s}$ to our data at $t = -0.33$ GeV^2 and $s/M^2 = 11$ for example gives $A = 14$ mb/GeV^2 and $B = 42$ mb/GeV .

The kinematic region of reaction (1) covered by our experiment is such that $s >> M^2 >> m^2$ and t is small. It has been suggested[5,6] that in this region it may be possible to describe this reaction by a triple Regge diagram which leads to the following expression for the invariant cross section

$$\frac{sd^2\sigma}{dtdM^2} = \frac{s_o}{s}\sum_{ijk} G_{ijk}(t)\left(\frac{s}{M^2}\right)^{\alpha_i(t)+\alpha_j(t)}\left(\frac{M^2}{s_o}\right)^{\alpha_k(0)} \tag{5}$$

where $s_o = 1\ GeV^2$. In general all possible combinations ijk where i,j,k are the Pomeranchuk ($\alpha_P = 1 + 0.5t$) or the leading meson trajectories ($\alpha_R = 0.5 + t$) can contribute to Eq. (5). There have been many theoretical conjectures concerning the relative importance of these contributions[7,8] and fits to sub NAL and ISR data have been attempted using only one[9] or two[10,11] terms in expression (5).

We have fitted our four spectra simultaneously with the triple Regge formula (5) and we conclude that we need at least three terms (PPP, PPR, RRP) and that at least one of the couplings G_{PPP} or G_{PPR} must be a function of t. The results of four fits to our data with different parametrizations for the t dependence are shown in Table I. We conclude that on the basis of our data alone, we cannot distinguish between the last three solutions. We have extrapolated the last three fits of Table I to the data of Albrow et al.[11] at $s = 1995\ GeV^2$, $|t| \geq 0.6$ GeV/c. The second solution listed in Table I is in poor agreement with the above data whereas the last two give a reasonable description. In view of the theoretical arguments[12] for $G_{PPP} = 0$ at $t = 0$, we conclude that $G_{PPP} = 23|t|e^{5.9t}$, $G_{PPR} = 2.5$, $G_{RRP} = 42\ mb/GeV^2$ is our preferred solution. The resulting fit to out data is shown in Fig. 2.

TABLE I. Triple Regge couplings in mb/GeV^2 from fits of Eq. (5) to our data (29 degrees of freedom).

G_{PPP}	G_{PPR}	G_{RRP}	χ^2
0.80	2.5	44	62
0.88	$12\ e^{4.0t}$	42	23
$3.2\ e^{3.3t}$	2.5	42	21
$23\|t\|e^{5.9t}$	2.5	42	21

Recently, Paige and Wang[13] have used the triple Regge formula (5) to fit data on $\pi^- + p \to p + X$ at 25 and 40 GeV/c and $t = -0.26$ GeV/c. They also conclude that the PPP, PPR and RRP terms are needed. Evaluating our preferred solution at $t = -0.26$ GeV/c we find that our couplings are in the same relative ratios as theirs. Furthermore the two sets of couplings are to within 10% in the ratio of the total cross sections for $\pi^- p$ and pp scattering, in excellent agreement[14] with factorization.

Summarizing, we have measured the s dependence of the invariant cross section for $p + p \to p + X$ in a restricted region of phase space near the kinematical limit. In the context of the triple Regge formalism, we establish the presence of at least three

terms in expansion (5). These terms are PPP, PPR and RRP. Furthermore at least one of the couplings G_{PPP} or G_{PPR} must be a function of t. The above interpretation of our data relies on the assumption, supported by experimental evidence, that the invariant cross section for $p + p \rightarrow \pi^{\pm} + X$ is independent of energy in our kinematical region.

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FIGURE CAPTIONS

Fig. 1 Spectrometer setup inside NAL main ring (not to scale). The spectrometer angle to the beam can be varied between 55° and 65°. The defining counter C_4 is 2.5 m from the target and subtends 5×10^{-4} sr.

Fig. 2 Our data plotted as a function of s at fixed t and s/M^2. The curves are a fit (fourth line of Table I) of the triple Regge formula (5) to all four spectra simultaneously.

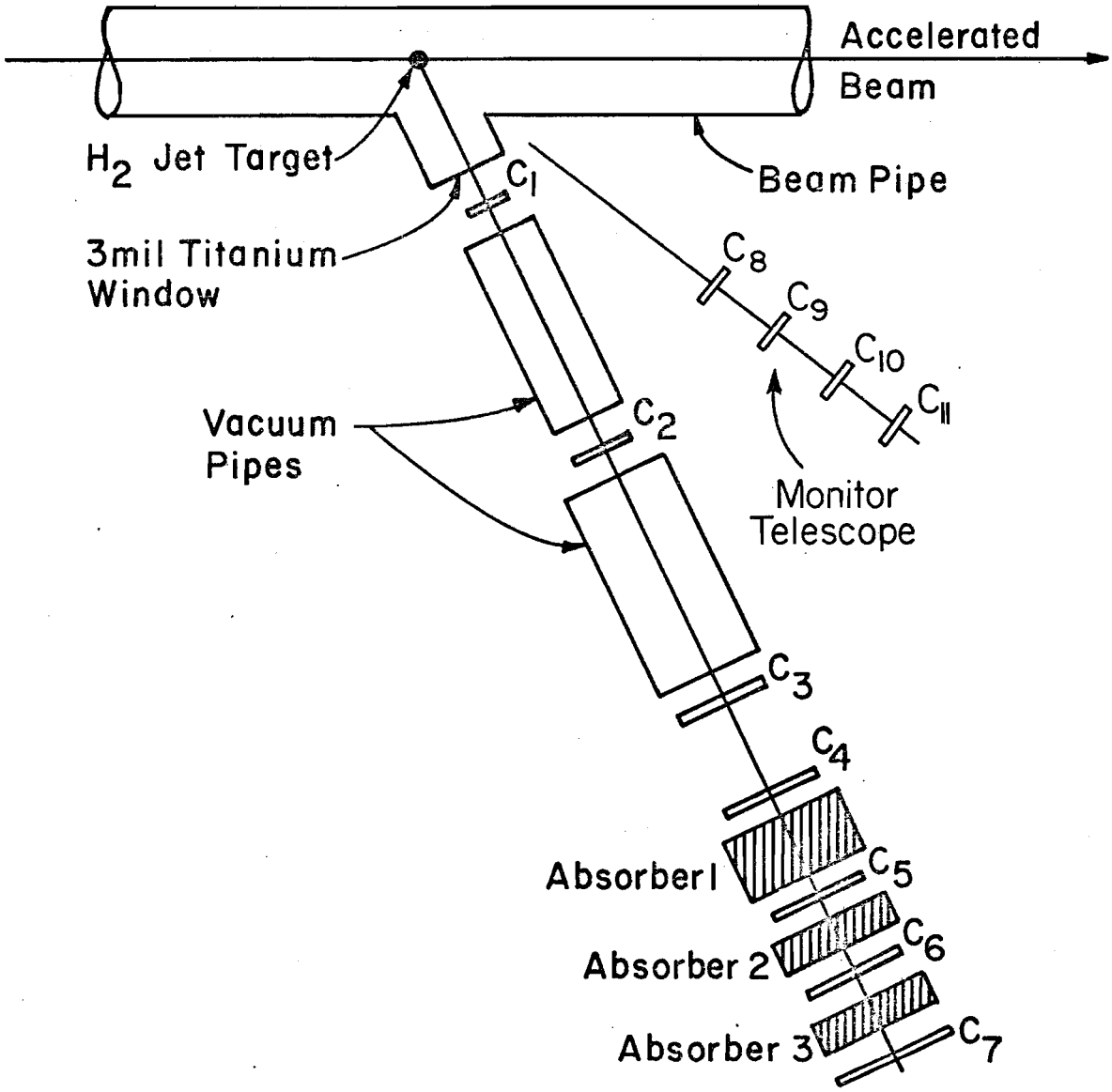
Accelerated
Beam
H_2 Jet Target
Beam Pipe
C_1
3mil Titanium
Window
C_8
C_9
C_{10}
C_{11}
Vacuum
Pipes
C_2
Monitor
Telescope
C_3
C_4
Absorber I
C_5
Absorber 2
C_6
Absorber 3
C_7

Fig. 1

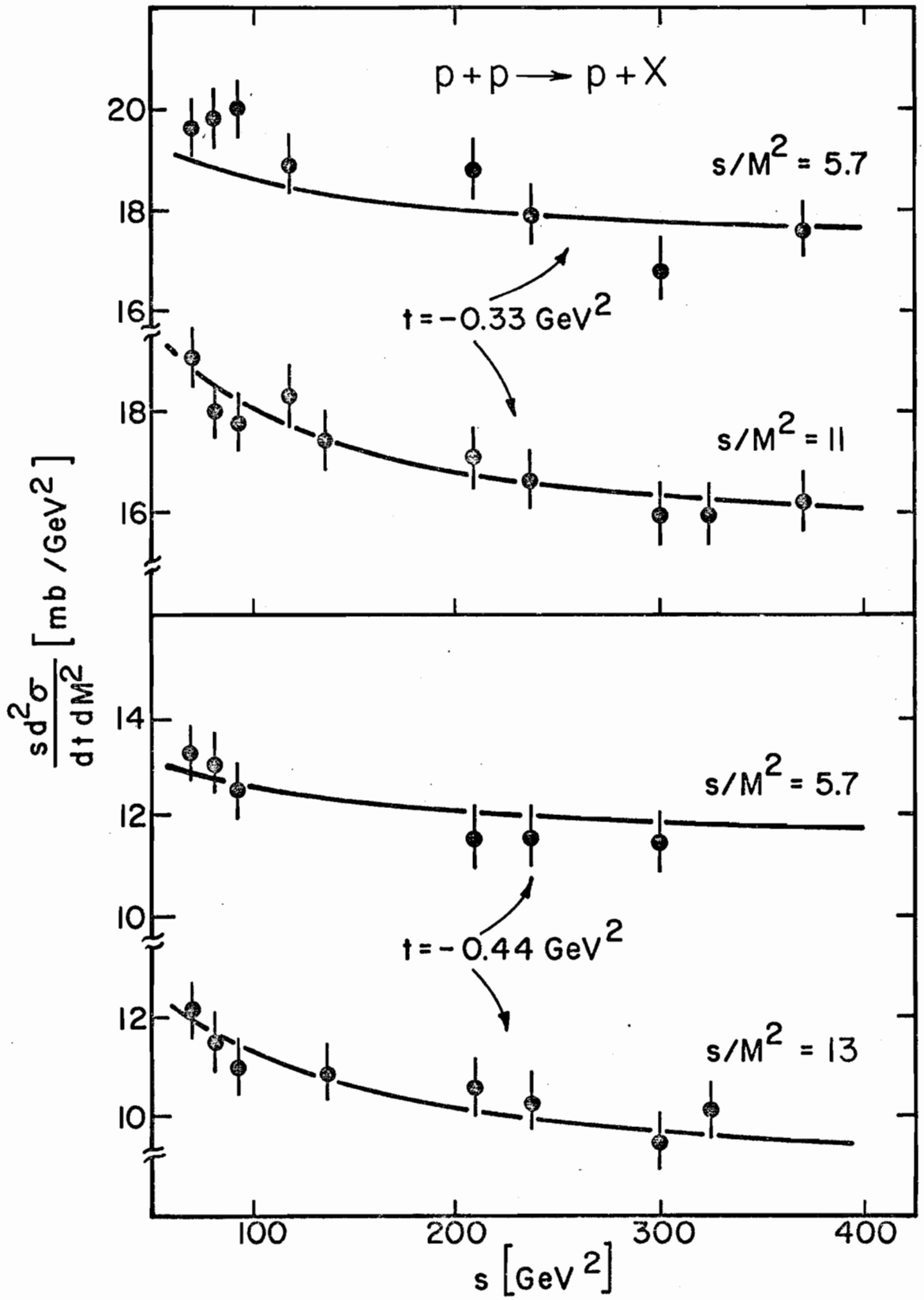
p + p → p + X
s/M² = 5.7
t = −0.33 GeV²
s/M² = 11
s/M² = 5.7
t = −0.44 GeV²
s/M² = 13
20
18
16
18
16
14
12
10
12
10
100
200
300
400
s [GeV²]
s d²σ / dt dM² [mb /GeV²]

Fig. 2