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VENEZIANO MODEL FOR $np \to pn$ AND $p\bar{p} \to n\bar{n}$ SCATTERING AND PARITY DOUBLET*

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ABSTRACT

The experimental $np \to pn$ and $p\bar{p} \to n\bar{n}$ differential cross-section data demand that there be opposite parity partners of exchange-degenerate π and B in order to have a sharp peak at $t = 0$. The invariant amplitudes, free from kinematic singularities, are constructed in Veneziano representation to show conspiracy relations in helicity amplitudes for each isotopic spin $I = 0$ and $I = 1$ demanded by the sharp forward peak in experimental $\frac{d\sigma}{dt}$. Since parity partners ρ and A_2 do not exist in nature, the usual Regge contribution due to exchange-degenerate ρ and A_2 exchange is employed, reducing thereby the number of parameters in residues and trajectories. The Veneziano-type t-dependent gamma function residue is introduced here.

INTRODUCTION

The data on $pn \rightarrow np$[1,2] $\frac{d\sigma}{dt}$ display a sharp peak at $t = 0$, whereas $p\bar{p} \rightarrow n\bar{n}$[3,4] has a much wider peak with roughly the same value at $t = 0$. This forward peak demands interpretation in terms of the lightest particle exchange apart from exchange of other particles that are expected to play equally important roles for large values of t. The lightest particle is the π meson, whose residue[5] is known to vanish at $t = 0$. Therefore, instead of contributing a sharp peak in the forward direction the π contributes a strong narrow minimum at $t = 0$--quite unlike experiment. Arbab and Dash[6] and Phillips[7] independently studied $pn \rightarrow np$ and $p\bar{p} \rightarrow n\bar{n}$ within the framework of Regge pole phenomenology, taking into consideration that π is a member of an $M = 1$ parity doublet.[8] The pion conspires with its opposite-parity partner (physically unknown) in such a way that the helicity-flip amplitude vanishes at $t = 0$, whereas the nonhelicity flip amplitude does not vanish at $t = 0$. Thus their works could reproduce the sharp toward peak at $t = 0$. In our earlier work, "Simpler Veneziano Model for np Charge-Exchange Scattering," only an $M = 0$ pion and an $M = 1$ pion parity doublet with a corresponding exchange-degenerate B were considered to give rise to a sharp peak in $\frac{d\sigma}{dt}$ at $t = 0$, yielding qualitative agreement with the experimental data. That model was valid for small t only, since the exchange of other massive particles was not taken into consideration for $\frac{d\sigma}{dt}$. Also the helicity amplitudes, not free of kinematic singularities, were expressed in Veneziano representation. Here we start from invariant amplitudes free of kinematic singularities that obey crossing symmetries of dynamical variables. Though our parameterization is not unique, helicity amplitudes deduced from invariant amplitudes are able to show conspiracy relations in a natural way, and new features are exhibited. In the scattering of non-zero-spin particles in Veneziano representation the parity doublet occurs in pairs. The opposite-parity[9] partners of the exchange-degenerate π and B are brought into the picture here to show conspiracy relations. Since it is not possible to kill the unwanted opposite-parity partners of exchange-degenerate ρ and A_2, the usual Regge contribution with Veneziano-type t-dependent gamma function residue is introduced. Only four adjustable parameters in residue functions are introduced. Thus our work is able to give qualitative and, to a great extent, quantitative agreement with experimental results, whereas earlier works by Arbab and Dash[6] and Phillips[7] required many adjustable parameters to fit the data.

FORMULAS AND PARAMETERIZATION

The Veneziano representation[10] for any amplitude incorporates the properties of resonance in one-channel energy and related asymptotic behavior in the crossed-channel energy for linearly rising trajectories. We make a simple Veneziano-type ansatz for the "five independent invariant amplitudes" for the process $NN \to NN$ and $N\bar{N} \to N\bar{N}$ for each isotopic spin $I = 0$ and $I = 1$. In $NN \to NN$, the resonance structures for t and u channels are the same and there is no s-channel resonance of exotic quantum numbers, whereas in $NN \to NN$, the resonance structures for t and s channels are the same and there is no u-channel resonance of exotic quantum numbers.

The invariant amplitudes for the process $p\bar{p} \to n\bar{n}$ can be obtained by crossing $s \longleftrightarrow u$ from the invariant amplitudes for the process $np \to pn$. The helicity amplitudes are related linearly to the invariant amplitudes. Since the parity doublet occurs in pairs, for each invariant amplitude, two linearly independent terms are considered when exchange-degenerate π and B and their opposite-parity partners c and B_c are exchanged. We get similar asymptotic behavior of helicity amplitudes: Phillips[7] obtained expressions[9] for the helicity amplitudes for $np \to pn$.

In $pn \to np$, the usual t-channel π-B exchange contributes only to ϕ_2 and ϕ_4 with the same magnitude and the same sign, and its residue vanishes at $t = 0$, whereas the u-channel π-B contributes only to ϕ_2 and ϕ_3 with the same magnitude and the opposite sign, and its residue vanishes at $u = 0$.

Let us denote $\frac{\Gamma[-\alpha(t)]\Gamma[-\alpha(u)]}{\Gamma[-\alpha(t) - \alpha(u)]}$ by $A[\alpha(t), \alpha(u)]$, $\frac{\Gamma[1 - \alpha(t)]\,\Gamma[1 - \alpha(u)]}{\Gamma[1 - \alpha(t) - \alpha(u)]}$ by $B[\alpha(t), \alpha(u)]$ and $\frac{\Gamma[1 - \alpha(t)]\,\Gamma[1 - \alpha(u)]}{\Gamma[2 - \alpha(t) - \alpha(u)]}[\alpha(t) - \alpha(u)]$ by $C[\alpha(t), \alpha(u)]$. The invariant amplitudes $G_i^T(s,t,u)$ for $NN \to NN$ satisfy the crossing symmetries

$$G_i^T(s,t,u) = (-1)^{i+T}\, G_i^T(s,u,t), \tag{1}$$

where $T = 0,1$ and $i = 1,2,3,4$, and 5. The invariant-amplitudes for the exchange of π-B and c-B_c are given by

$$[G_1(s,t,u)]_{T=0} = [G_5(s,t,u)]_{T=0}$$
$$= \frac{3}{2}\beta' \frac{A[\alpha(t), \alpha(u)][\alpha(t) - \alpha(u)]}{\alpha(t) + \alpha(u)} + \frac{3}{2}\frac{\beta''}{\alpha(0)} C[\alpha(t), \alpha(u)] , \tag{2}$$

$$[G_2(s,t,u)]_{T=0} = -\frac{3}{2}\beta' A[\alpha(t), \alpha(u)] + \frac{3}{2}\frac{\beta''}{\alpha(0)} B[\alpha(t), \alpha(u)] , \tag{3}$$

$$[G_3(s,t,u)]_{T=0} = -\frac{3}{2}\beta' \frac{A[\alpha(t), \alpha(u)][\alpha(t) - \alpha(u)]}{\alpha(t) + \alpha(u)} + \frac{3}{2}\frac{\beta''}{\alpha(0)} C[\alpha(t),\alpha(u)], \tag{4}$$

$$[G_4(s,t,u)]_{T=0} = \frac{3}{2}\beta' A[\alpha(t), \alpha(u)] + \frac{3}{2}\frac{\beta''}{\alpha(0)} B[\alpha(t), \alpha(u)], \tag{5}$$

$$[G_1(s,t,u)_{T=1} = [G_5(s,t,u)]_{T=1} = \frac{\beta'}{2} A[\alpha(t),\alpha(u)] - \frac{1}{2}\frac{\beta''}{\alpha(0)} B[\alpha(t),\alpha(u)], \tag{6}$$

$$[G_2(s,t,u)]_{T=1} = -\frac{\beta'}{2}\frac{A[\alpha(t),\alpha(u)][\alpha(t), -\alpha(u)]}{\alpha(t)+\alpha(u)} - \frac{1}{2}\frac{\beta''}{\alpha(0)} C[\alpha(t),\alpha(u)] , \tag{7}$$

$$[G_3(s,t,u)]_{T=1} = -\frac{\beta'}{2} A[\alpha(t), \alpha(u)] - \frac{1}{2}\frac{\beta''}{\alpha(0)} B[\alpha(t), \alpha(u)], \tag{8}$$

and

$$[G_4(s,t,u)]_{T=1} = \frac{\beta'}{2}\frac{A[\alpha(t),\alpha(u)][\alpha(t)-\alpha(u)]}{\alpha(t)+\alpha(u)} - \frac{1}{2}\frac{\beta''}{\alpha(0)} C[\alpha(t),\alpha(u)] . \tag{9}$$

Using Eq. (2.20) from Muzinich[5] for the helicity amplitudes, one gets

$$[\phi_3(s,t,)]_{T=0,1}$$

$$= [\phi_1(s,t)]_{T=0,1} \xrightarrow[\text{large s}]{\text{fixed t}} \left(-\frac{3}{2}, \frac{1}{2}\right)\left(-\frac{\pi\beta' tb}{2}\right)\left(\frac{m^2}{s}\right)\frac{s^{\frac{1}{2}}(bs)^{\alpha(t)-1}}{\sin \pi\alpha(t)\alpha(0)\Gamma[\alpha(t)]}$$

$$+ \left(-\frac{3}{2}, \frac{1}{2}\right) (-2\pi bm^2\beta'') \frac{s^{\frac{1}{2}}(bs)^{\alpha(t)-1}}{\sin \pi\alpha(t)\ \alpha(0)\Gamma[\alpha(t)]} , \tag{10}$$

$$[\phi_2(s,t)]_{T=0,1} \xrightarrow[\text{large s}]{\text{fixed t}} \left(-\frac{3}{2}, \frac{1}{2}\right)\left(-\frac{\pi\beta' tb}{2}\right)\frac{s^{\frac{1}{2}}(bs)^{\alpha(t)-1}}{\sin \pi\alpha(t)\Gamma[\alpha(t)+1]}$$

$$+ \left(-\frac{3}{2}, \frac{1}{2}\right)\left(-\frac{\pi bs\beta'' t}{2p^2}\right)\frac{s^{\frac{1}{2}}(bs)^{\alpha(t)-1}}{\sin \pi\alpha(t)\ \alpha(0)\ \Gamma[\alpha(t)]} , \tag{11}$$

$$[\phi_4(s,t)]_{T=0,1} \xrightarrow[\text{large s}]{\text{fixed t}} \left(-\frac{3}{2},\frac{1}{2}\right)\left(-\frac{\pi\beta' tb}{2}\right)\frac{s^{\frac{1}{2}}(bs)^{\alpha(t)-1}}{\sin \pi\alpha(t)\ \Gamma[\alpha(t)+1]}$$

$$- \left(-\frac{3}{2},\frac{1}{2}\right)\left(-\frac{\pi bs\beta'' t}{2p^2}\right)\frac{s^{\frac{1}{2}}(bs)^{\alpha(t)-1}}{\sin \pi\alpha(t)\ \alpha(0)\ \Gamma[\alpha(t)]} , \tag{12}$$

$$[\phi_5(s,t)]_{T=0,1} \xrightarrow[\text{large } s]{\text{fixed } t} -\left(-\frac{3}{2},\frac{1}{2}\right)\left(-\frac{\pi b s \beta'' t}{2p^2}\right)\left(1+\frac{s}{m^2}\right)^{\frac{1}{2}}$$

$$\times \quad \frac{m(bs)^{\alpha(t)-1}}{\sin \pi\alpha(t)\ \alpha(0)\ \Gamma[\alpha(t)]} . \qquad (13)$$

The conspiracy relation imposes two conditions on residues and trajectories at $t = 0$. The t-dependent residues should not be allowed to vanish at $t = 0$. This requirement that they not vanish is satisfied if $\left(-\frac{\pi\beta t b}{2}\right)$ and $\left(-\frac{\pi b s\beta'' t}{2p^2}\right)$ are replaced by $\beta_t \neq 0$ at $t = 0$, and the trajectories of the two terms are equal at $t = 0$. On substitution, one finds that the helicity-flip amplitude $[\phi_4(s,t)]_{T=0,1}$ vanishes at $t = 0$ and the non-helicity-flip amplitude $[\phi_2(s,t)]_{T=0,1}$ does not vanish at $t = 0$. If $-2\pi b m^2\beta''$ is denoted by β, one can have only two independent residue parameters. By adjusting them suitably, one can obtain a sharp peak at $t = 0$. When πB and cB_c are exchanged in the t channel, the t-channel helicity amplitudes, with residues β and β_t, are therefore given by

$$[\phi_1(s,t)]_{T=0,1} \sim [\phi_3(s,t)]_{T=0,1}$$

$$= \left(-\frac{3}{2},\frac{1}{2}\right) \beta_t \left(\frac{m^2}{s}\right) \frac{s^{\frac{1}{2}}(bs)^{\alpha(t)-1}}{\sin \pi\alpha(t)\alpha(0)\Gamma[\alpha(t)]}$$

$$+ \left(-\frac{3}{2},\frac{1}{2}\right) \beta \frac{s^{\frac{1}{2}}(bs)^{\alpha(t)-1}}{\sin \pi\alpha(t)\alpha(0)\Gamma[\alpha(t)]} , \qquad (14)$$

$$[\phi_2(s,t)]_{T=0,1} \sim \left(-\frac{3}{2},\frac{1}{2}\right) \beta_t \frac{s^{\frac{1}{2}}(bs)^{\alpha(t)-1}}{\sin \pi\alpha(t)\Gamma[\alpha(t)+1]}$$

$$+ \left(-\frac{3}{2},\frac{1}{2}\right) \beta_t \frac{s^{\frac{1}{2}}(bs)^{\alpha(t)-1}}{\sin \pi\alpha(t)\alpha(0)\Gamma[\alpha(t)]} , \tag{15}$$

$$[\phi_4(s,t)]_{T=0,1} \sim \left(-\frac{3}{2},\frac{1}{2}\right) \beta_t \frac{s^{\frac{1}{2}}(bs)^{\alpha(t)-1}}{\sin \pi\alpha(t)\Gamma[\alpha(t)+1]}$$

$$- \left(-\frac{3}{2},\frac{1}{2}\right) \beta_t \frac{s^{\frac{1}{2}}(bs)^{\alpha(t)-1}}{\sin \pi\alpha(t)\alpha(0)\Gamma[\alpha(t)]} , \tag{16}$$

$$[\phi_5(s,t)]_{T=0,1} \sim - \left(-\frac{3}{2},\frac{1}{2}\right) \beta_t \left(1 + \frac{s}{m^2}\right)^{\frac{1}{2}} \frac{m(bs)^{\alpha(t)-1}}{\sin \pi\alpha(t)\alpha(0)\Gamma[\alpha(t)]} . \tag{17}$$

Similarly, the helicity amplitudes when πB and cB_c are exchanged in the u channel are given by

$$[\phi_2(s,u)]_{T=0,1} \sim - \left(-\frac{3}{2},\frac{1}{2}\right) \beta_u \frac{s^{\frac{1}{2}}(bs)^{\alpha(u)-1}}{\sin \pi\alpha(u)\Gamma[\alpha(u)+1]}$$

$$- \left(-\frac{3}{2},\frac{1}{2}\right) \frac{\beta_u\, s^{\frac{1}{2}}(bs)^{\alpha(u)-1}}{\sin \pi\alpha(u)\alpha(0)\Gamma[\alpha(u)]} , \tag{18}$$

$$[\phi_3(s,u)]_{T=0,1} \sim \left(-\frac{3}{2},\frac{1}{2}\right) \beta_u \frac{s^{\frac{1}{2}}(bs)^{\alpha(u)-1}}{\sin \pi\alpha(u)\Gamma[\alpha(u)+1)]}$$

$$- \left(-\frac{3}{2},\frac{1}{2}\right) \frac{\beta_u\, s^{\frac{1}{2}}(bs)^{\alpha(u)-1}}{\sin \pi\alpha(u)\alpha(0)\Gamma[\alpha(u)]} . \tag{19}$$

The first- and second terms of each helicity amplitude look like Regge contributions because of exchange of π-B and c-B_c respectively, in the corresponding channels. The asymptotic behavior of all the terms in Veneziano representation looks similar to that in the Regge pole model except that the residues are dependent on gamma functions in the denominator. Therefore one can assume that helicity amplitudes due to exchange of exchange-degenerate ρ and A_2 should be given by[7,12]

$$[\phi_1(s,t)]_{T=0,1} = [\phi_3(s,t)]_{T=0,1}$$

$$\sim \left(-\frac{3}{2},\frac{1}{2}\right) \left(b_1 + \tau\alpha b_2\right)^2 \frac{s^{\frac{1}{2}}(bs)^{\alpha(t)-1}}{\sin \pi\alpha(t)\ \Gamma[\alpha(t)]} , \tag{20}$$

$$[\phi_2(s,t)]_{T=0,1} = - [\phi_4(s,t)]_{T=0,1}$$

$$\sim - \left(-\frac{3}{2},\frac{1}{2}\right) \tau(b_1 - \alpha b_2)^2 \frac{s^{\frac{1}{2}}(bs)^{\alpha(t)-1}}{\sin \pi\alpha(t)\Gamma[\alpha(t)]} , \tag{21}$$

$$[\phi_5(s,t)]_{T=0,1}$$

$$\sim - \left(-\frac{3}{2},\frac{1}{2}\right) \tau^{\frac{1}{2}}(b_1 + \tau\alpha b_2)(b_1 - \alpha b_2) \frac{s^{\frac{1}{2}}(bs)^{\alpha(t)-1}}{\sin \pi\alpha(t)\Gamma[\alpha(t)]} . \tag{22}$$

Here τ denotes $-\frac{t}{4m_N^2}$. We have, in general,

$$\phi_i^{x}(np \to pn) = \frac{1}{2} \left(\phi_i^{x}(s,t)_{I=0} - \phi_i^{x}(s,t)_{I=1}\right) \tag{23}$$

where x denotes symbolically the exchange of particles, say, π-B and c-B_c from Eqs. (14) through (17) and ρ-A_2 from Eqs. (20) through (22).

Also,

$$\phi_i^{\text{total}}(s,t) = \phi_i^1(s,t) + \phi_i^2(s,t) \tag{24}$$

where 1 and 2 denote particles (π-B and c-B_c) and (ρ-A_2) respectively. Therefore

$$\frac{d\sigma}{dt} = \frac{\pi}{2k^2}\left\{\sum_{i=1}^{4} |\phi_i^{\text{total}}|^2 + 4|\phi_5^{\text{total}}|^2\right\} \quad . \tag{25}$$

There is an analogous set of invariant amplitudes $G_i^T(u,t,s)$ for the $N\overline{N}$ channel obtained from the set $G_i^T(s,t,u)$ under the plausible assumption by crossing $s \leftrightarrow u$. There is also a set of amplitudes $\overline{\phi}$ linearly related in the same way to the invariant amplitudes $\overline{G}$ when p, E, etc. are replaced by $\overline{p}$, $\overline{E}$, etc. for the corresponding $N\overline{N}$ channel. For large s and fixed t, the form of each expression for the set $\overline{\phi}$ remains the same except that each term is multiplied by a factor $e^{-i\pi\alpha(t)}$, where $\alpha(t)$ is the corresponding trajectory of the exchange-degenerate particles exchanged. For the exchange of x particles $\overline{\phi}_i^x(p\overline{p} \to n\overline{n})$ are given by

$$\overline{\phi}_i^x(p\overline{p} \to n\overline{n}) = \frac{1}{2}\left[\overline{\phi}_i^x(s,t)_{I=0} - \overline{\phi}_i^x(s,t)_{I=1}\right] , \tag{26}$$

and

$$\overline{\phi}_i^{\text{total}}(s,t) = \overline{\phi}_i^1(s,t) + \overline{\phi}_i^2(s,t) , \tag{27}$$

where 1 and 2 denote particles (π-B and c-B_c) and (ρ-A_2) respectively. Therefore

$$\frac{d\sigma}{dt} = \frac{\pi}{2k^2}\left\{\sum_{i=1}^{4} |\bar{\phi}_i^{\,total}|^2 + 4|\bar{\phi}_5^{\,total}|^2\right\}. \tag{28}$$

The π-B, c-B_c, and ρ-A_2 trajectories are respectively

$$\begin{aligned} \alpha_{\pi\text{-}B}(t) &= -0.025 + 1.25\ t\ , \\ \alpha_{c\text{-}B_c}(t) &= -0.025 + 1.01\ t\ , \\ \alpha_{\rho\text{-}A_2}(t) &= 0.5 + t\ . \end{aligned} \tag{29}$$

DESCRIPTION OF THE FIT

There are all together 32 data for $np \rightarrow pn$ differential cross-sections at incident laboratory momentum 8 GeV/c. There is a systematic uncertainty of ±30% common to all values. There is an additional systematic uncertainty of ±15% for $-t > 0.143$ $(\text{GeV/c})^{-2}$. All these, apart from statistical errors are taken into consideration for the minimum value of χ^2. There are 19 data at incident laboratory momentum 5,6,7, and 9 GeV/c. The errors for the $p\bar{p} \rightarrow n\bar{n}$ differential cross-sections $\frac{d\sigma}{dt}$ were obtained by multiplying the statistical errors by a factor of 2.2. This rather arbitrary factor was a crude compromise between not including any systematic error at all and multiplying the statistical error by a factor of 4.78 as was done by G. Manning[2] etc. for $\frac{d\sigma}{dt}$.

Our calculated curve for $np \rightarrow pn$ $\frac{d\sigma}{dt}$ passes through the points within the error bar. The calculated curves at incident laboratory momentum 5, 6, and 7 GeV/c are in good agreement with experimental data from $t = 0$ to $t = -0.90$ $(\text{GeV/c})^2$. The calculated $\frac{d\sigma}{dt}$ curve at incident laboratory momentum 9 GeV/c for $p\bar{p} \rightarrow n\bar{n}$ is not in good agreement with experimental $\frac{d\sigma}{dt}$ even though the calculations have been multipled by 1.25. The χ^2 for both $np \rightarrow pn$ and $p\bar{p} \rightarrow n\bar{n}$ differential cross sections $\frac{d\sigma}{dt}$ is 146.04 for 108 data points. For minimum χ^2, β_t, β, b_1, and b_2 are given by

$$\beta_t \approx 1.24 \text{ mb } (\text{GeV/c})^{-2} ,$$

$$\beta \approx 0.12 \text{ mb } (\text{GeV/c})^{-2} ,$$

$$b_1 \approx 0.095 \text{ (mb)}^{\frac{1}{2}} (\text{GeV/c})^{-1} , \quad (30)$$

$$b_2 \approx 0.1 \text{ (mb)}^{\frac{1}{2}} (\text{GeV/c})^{-1} .$$

Figures 1 through 5 summarize the work of this investigation.

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FOOTNOTES AND REFERENCES

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FIGURE CAPTIONS

Fig. 1. $\frac{d\sigma}{dt}$ for np charge-exchange scattering at lab momentum 8 GeV/c. Data points are taken from Ref. 2.

Fig. 2. $\frac{d\sigma}{dt}$ for $p\bar{p}$ charge-exchange scattering at lab momentum 5 GeV/c. Data points are taken from Ref. 4.

Fig. 3. $\frac{d\sigma}{dt}$ for $p\bar{p}$ charge-exchange scattering at lab momentum 6 GeV/c. Data points are taken from Ref. 4.

Fig. 4. $\frac{d\sigma}{dt}$ for $p\bar{p}$ charge-exchange scattering at lab momentum 7 GeV/c. Data points are taken from Ref. 4.

Fig. 5. $\frac{d\sigma}{dt}$ for $p\bar{p}$ charge-exchange scattering at lab momentum 9 GeV/c. Data points are taken from Ref. 4.

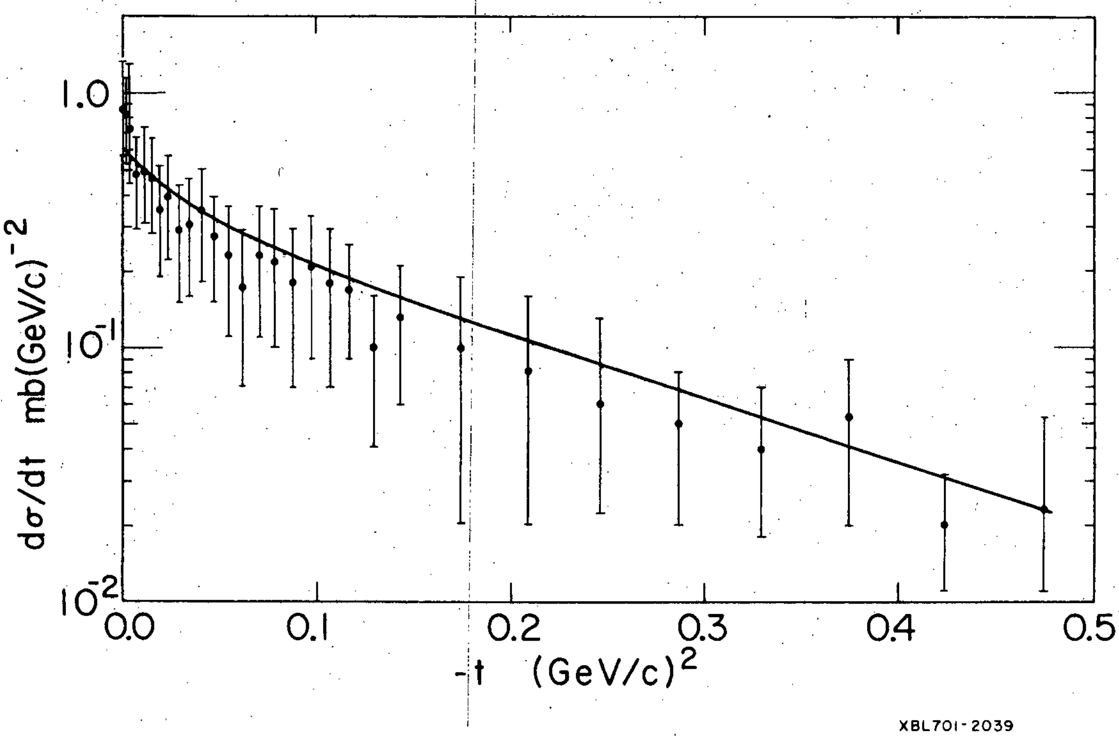

1.0
10^{-1}
10^{-2}
$d\sigma/dt$ mb(GeV/c)$^{-2}$
0.0
0.1
0.2
0.3
0.4
0.5
-t (GeV/c)^2
XBL701-2039

Fig. 1

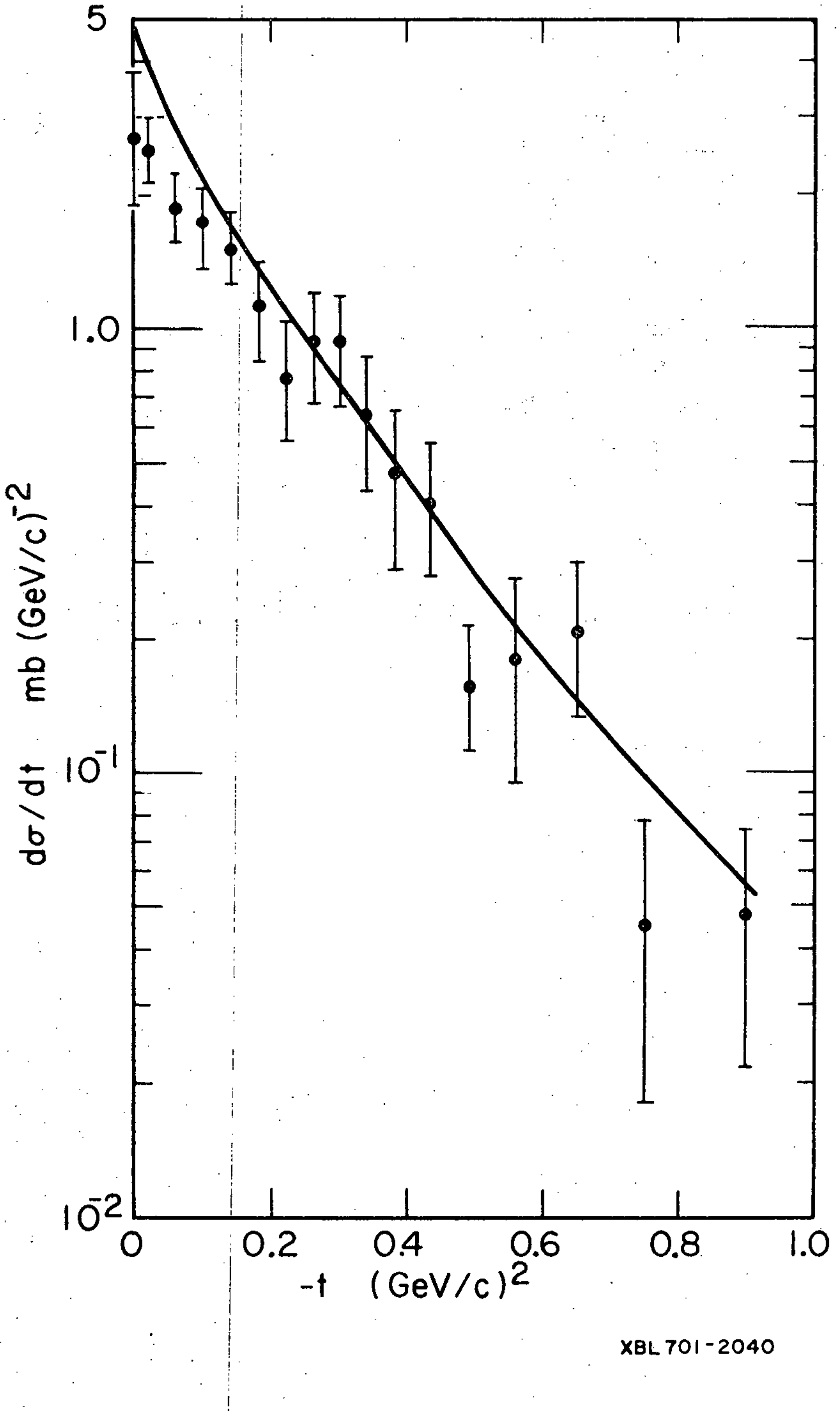

5
1.0
10^{-1}
10^{-2}
$d\sigma/dt$ mb $(GeV/c)^{-2}$
0
0.2
0.4
0.6
0.8
1.0
$-t$ $(GeV/c)^2$
XBL 701-2040

Fig. 2

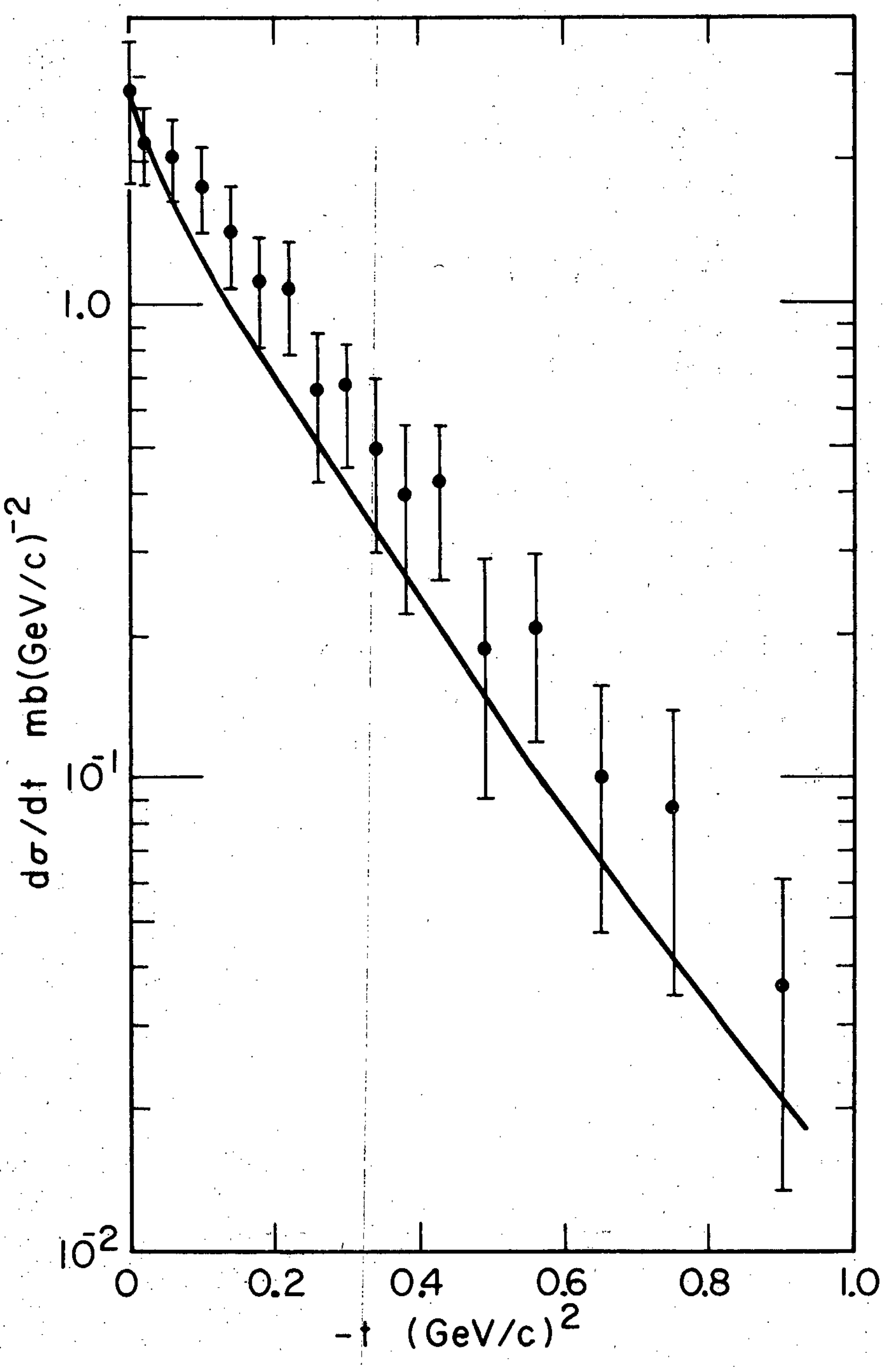
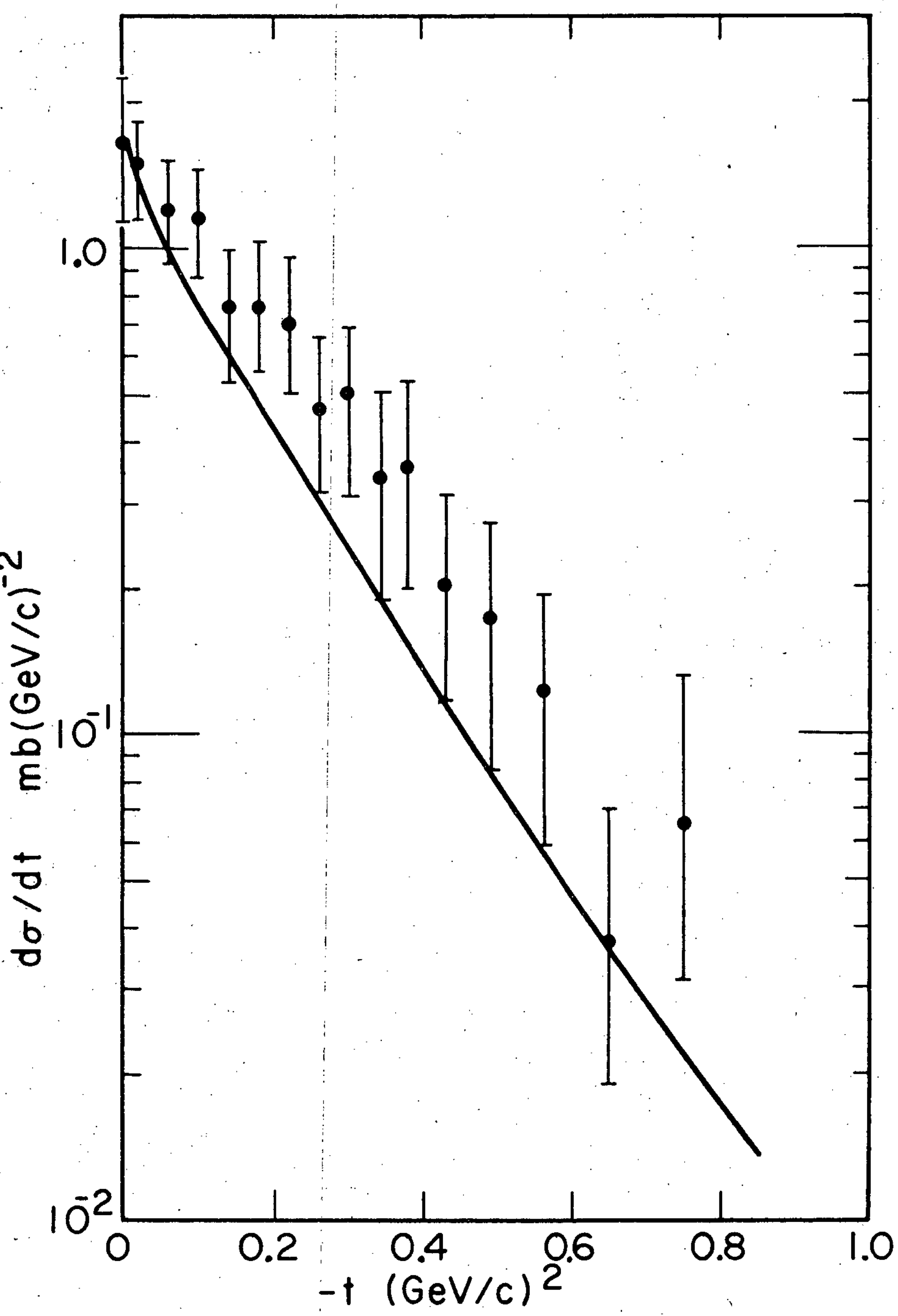

1.0
10^{-1}
10^{-2}
$d\sigma/dt$ mb$(GeV/c)^{-2}$
0
0.2
0.4
0.6
0.8
1.0
$-t$ $(GeV/c)^2$
XBL701-2041

Fig. 3



XBL701-2042

Fig. 4

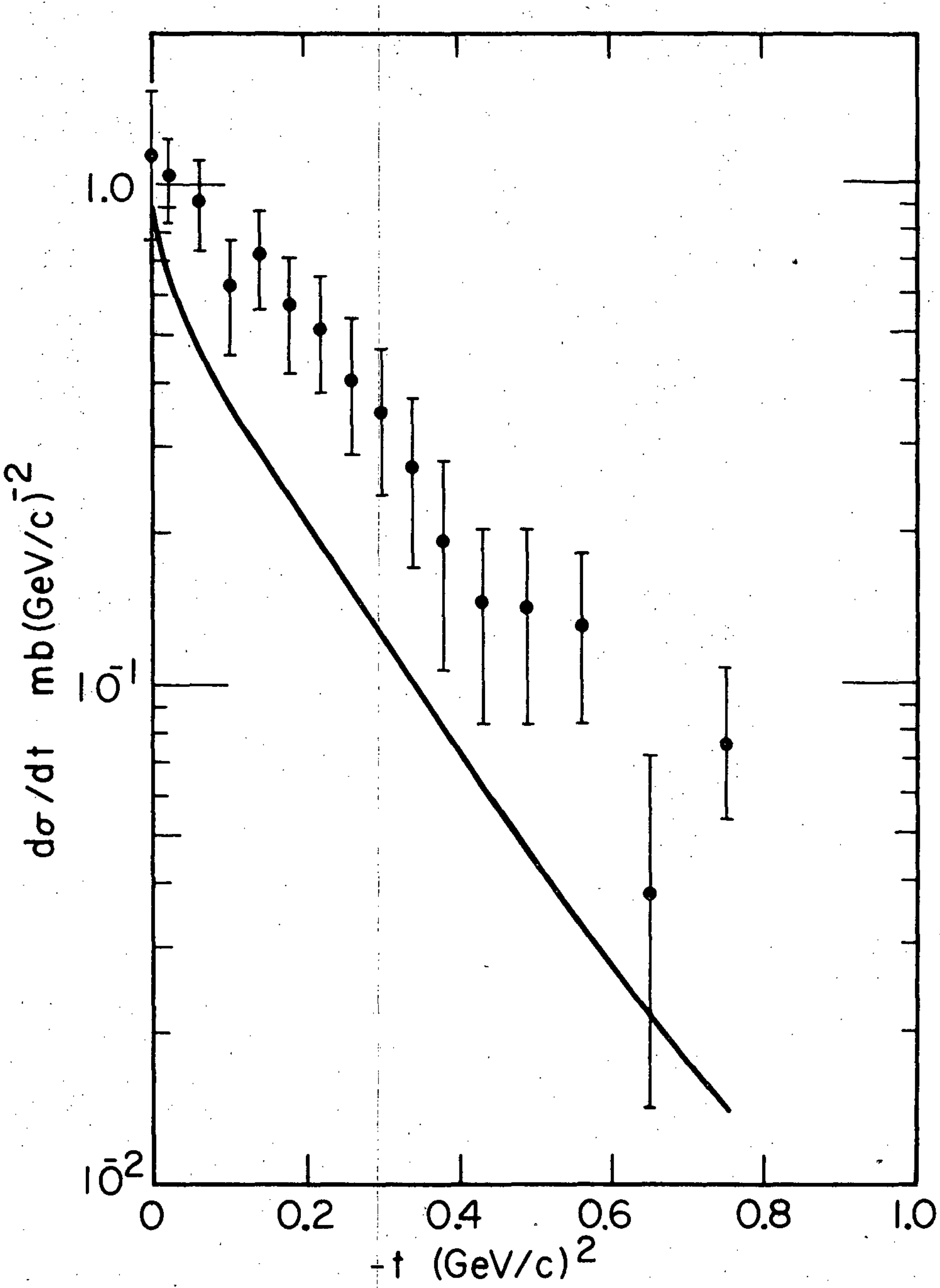


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Fig. 5

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