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the Dependence on the Vector Meson Mass Squared

by



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<sup>+</sup>Part of this work has been done during one of the authors (C.I.) stay at DESY during the summer of 1973.

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Abstract:

We propose a new form of VMD which relates the reactions  $\pi N \rightarrow \rho N$  and  $\gamma N \rightarrow \pi N$ . Our form fits the experimental results within errors. As our restriction is strong enough, we can discuss the  $k_{\mu}^2$ -dependence. Unexpectedly the  $k_{\mu}^2$ -dependence is larger and this may suggest the necessity of generalized vector dominance.

## 1. Introduction

It is well known that vector meson dominance<sup>1)</sup> (VMD) works well in the region  $|k_\mu^2| \leq m_\rho^2$  and explains the experiment within a factor of 2. On the other hand,  $e^+e^-$  annihilation experiments<sup>2)</sup> force to generalize VMD by introducing more vector mesons than the originally observed  $\rho$ ,  $\omega$  and  $\phi$ . At first, the application of VMD<sup>3)</sup> to the following processes

$$" \gamma " + N \rightarrow \pi + N$$

$$\pi + N \rightarrow \nu + N$$

succeeded quite well and the different angular distribution was explained by considering the helicity dependence of the cross section. However, more detailed analysis on pion photoproduction by linearly polarized photon<sup>4)</sup> shows some contradictions to VMD.

In this note we propose a new form of VMD, and by comparing with the experiment we discuss the  $k_\mu^2$ -dependence of the amplitude (observable quantities). We use the unitarity relation, and describe the observable quantities in terms of the three particle forward scattering amplitudes<sup>5)</sup> and then we apply Cho-Sakurai type<sup>6)</sup> arguments to these discontinuities. That is, we expand the discontinuities up to the first order of  $k_\mu^2$  and apply the gauge condition in each order of  $k_\mu^2$ . As the discontinuities themselves are related to the observable quantities linearly, our new form of VMD is more useful than the Cho-Sakurai type argument. For example, in our form we need not to know the experimental results of the complete experiment on pion photoproduction, moreover, we have enough restriction to discuss the  $k_\mu^2$ -dependence in our form.

In the next section we explain the formalism of the new form of VMD. In the third section we analyze the experiments using our formula and discuss the  $k_\mu^2$ -dependence of the amplitude. In the final section a short discussion is given

## 2. New Relations of Vector Meson Dominance<sup>+</sup>

In this section we show the new relations between the processes

$$" \gamma " + N \rightarrow \pi + N \tag{1}$$

$$\pi + N \rightarrow \nu + N \tag{2}$$

<sup>+</sup>The result in this section is a special case of that for the inclusive reaction derived in Ref.5).

using VMD. The derivation of the new relations becomes possible by representing the cross sections and the vector meson density matrix elements of these processes, (1) and (2), in terms of the discontinuities of the three particle forward scattering amplitudes;

$$M_{\mu_1 \nu_1}^{\mu_2 \nu_2}(\pi\pi) \equiv \text{Disc} \langle p \nu_2, k \mu_2; q | M | p \nu_1, k \mu_1; q \rangle, \quad (3)$$

$$M_{\mu_2 \nu_1}^{\nu_2 \mu_1}(\pi\nu) \equiv \text{Disc} \langle p \nu_2, q; k \mu_1 | M | p \nu_1, q; k \mu_2 \rangle, \quad (4)$$

where  $q$ ,  $p$  and  $k$  are the energy-momentum four-vector of pion, initial nucleon and vector particle, respectively,  $\nu_i$  and  $\mu_i$  represent the helicity of nucleon and vector particle, respectively.

When the nucleon is unpolarized, we represent the discontinuities (3) and (4) as the sum of the following ten (non-gauge invariant) terms;

$$\begin{aligned} \text{Disc } T &= \varepsilon_{\mu_2}^* M_{\mu_1}^{\mu_2} \varepsilon^{\mu_1} \\ &= A_+ a_+ + B b + C c + G g + F_+ f_+ \\ &\quad + i \bar{F} f_- + J_+ j_+ + i J_- j_- + H_+ h_+ + i H_- h_-, \end{aligned} \quad (5)$$

where<sup>+</sup>

$$a_+ = (\varepsilon^* \varepsilon) = \frac{1}{2} [(\gamma \varepsilon^*)(\gamma \varepsilon) + (\gamma \varepsilon)(\gamma \varepsilon^*)], \quad (6)$$

$$b = (p \varepsilon^*)(p \varepsilon), \quad (7)$$

$$c = (q \varepsilon^*)(q \varepsilon), \quad (8)$$

$$g = (k \varepsilon^*)(k \varepsilon), \quad (9)$$

$$f_+ = (p \varepsilon^*)(q \varepsilon) + (q \varepsilon^*)(p \varepsilon), \quad (10)$$

$$f_- = (p \varepsilon^*)(q \varepsilon) - (q \varepsilon^*)(p \varepsilon), \quad (11)$$

<sup>+</sup> $\varepsilon$  is the polarization vector of photon (vector meson), and we use the abbreviation  $(a b) \equiv \vec{a} \cdot \vec{b} - a_0 b_0$ .

$$h_+ = (kE^*)(qE) + (qE^*)(kE) , \quad (12)$$

$$h_- = (kE^*)(qE) - (qE^*)(kE) , \quad (13)$$

$$j_+ = (kE^*)(pE) + (pE^*)(kE) , \quad (14)$$

$$j_- = (kE^*)(pE) - (pE^*)(kE) . \quad (15)$$

In the expression (5) all the coefficients  $A_+$ ,  $B$ , ... are taken to be real.

Gauge invariance requires the relation

$$k_{\mu_2} M_{\mu_1}^{\mu_2} \epsilon^{\mu_1} = \epsilon_{\mu_2}^* M_{\mu_1}^{\mu_2} k^{\mu_1} = 0 , \quad (16)$$

that is, the coefficients satisfy the following equations

$$A_+ + k_\mu^2 G + (kq)H_+ + (kp)J_+ = 0 , \quad (17)$$

$$(kq)H_- + (kp)J_- = 0 , \quad (18)$$

$$(kq)C + (kp)F_+ + k_\mu^2 H_+ = 0 , \quad (19)$$

$$(kp)F_- + k_\mu^2 H_- = 0 , \quad (20)$$

$$(kp)B + (kq)F_+ + k_\mu^2 J_+ = 0 . \quad (21)$$

Then we can choose the following five discontinuities as independent;

$A_+$ ,  $C$ ,  $B$ ,  $F_+$  and  $F_-$ .

The cross sections and the vector meson density matrix elements  $\rho_{ij}$  are given in terms of these Lorentz invariant discontinuities as follows:

(i)  $\pi + N \rightarrow V + N$

$$\rho_{ii} \left( \frac{d^3\sigma}{dR} \right)^{\pi V} = \frac{1}{4Wq} [ 2A_+ + q^2 \sin^2\theta B + q^2 \sin^2\theta C - 2q^2 \sin^2\theta F_+ ] , \quad (22)$$

$$\rho_{00} \left( \frac{d^3\sigma}{dk} \right)^{\pi\nu} = \frac{1}{4Wq} \left[ 2A_+ + \frac{2(qk_0 \cos\theta + kp_0)^2}{m_\pi^2} B + \frac{2(qk_0 \cos\theta - kq_0)^2}{m_\pi^2} C \right. \\ \left. - \frac{4(qk_0 \cos\theta + kp_0)(qk_0 \cos\theta - kq_0)}{m_\pi^2} F_+ \right], \quad (23)$$

$$\rho_{1-1} \left( \frac{d^3\sigma}{dk} \right)^{\pi\nu} = \frac{1}{4Wq} \left[ -q^2 \sin^2\theta B - q^2 \sin^2\theta C + 2q^2 \sin^2\theta F_+ \right], \quad (24)$$

$$\text{Re } \rho_{10} \left( \frac{d^3\sigma}{dk} \right)^{\pi\nu} = \frac{\sqrt{2} q \sin\theta}{4Wq} \left[ \frac{qk_0 \cos\theta + kp_0}{m_\pi} B + \frac{qk_0 \cos\theta - kq_0}{m_\pi} C \right. \\ \left. - \frac{2qk_0 \cos\theta - kq_0 + kp_0}{m_\pi} F_+ \right], \quad (25)$$

$$\text{Im } \rho_{10} \left( \frac{d^3\sigma}{dk} \right)^{\pi\nu} = - \frac{\sqrt{2} q \sin\theta}{4Wq} \frac{k(p_0 + k_0)}{m_\pi} F_-, \quad (26)$$

where

$$dk = \frac{d^3k}{2k_0}, \quad (27)$$

and  $q$ ,  $p$  and  $k$  are magnitudes of momentum of pion, initial nucleon and vector meson in the CM system, respectively, and  $q_0$ ,  $p_0$  and  $k_0$  are the energies of the corresponding particles.  $W$  is the total energy and  $\theta$  is the scattering angle in the CM system.

(ii)  $\Upsilon + N \rightarrow \pi + N$

$$\left( \frac{d^3\sigma}{dq} \right)_{\perp}^{\Upsilon\pi} = \frac{1}{2} \left[ \left( \frac{d^3\sigma}{dq} \right)_{\parallel}^{\Upsilon\pi} + \left( \frac{d^3\sigma}{dq} \right)_{\parallel-1}^{\Upsilon\pi} \right] \\ = \frac{1}{4WR} A_+, \quad (28)$$

$$\left( \frac{d^3\sigma}{dq} \right)_{\parallel}^{\Upsilon\pi} = \frac{1}{2} \left[ \left( \frac{d^3\sigma}{dq} \right)_{\parallel}^{\Upsilon\pi} - \left( \frac{d^3\sigma}{dq} \right)_{\parallel-1}^{\Upsilon\pi} \right] \\ = \frac{1}{4WR} (A_+ + q^2 \sin^2\theta C). \quad (29)$$



(iii)  $e + N \rightarrow e + \pi + N$ 

$$\left( \frac{d^6\sigma}{dE'd\Omega_e d\Omega_\pi} \right) = \Gamma_t \left[ \sigma_{11} + \epsilon \sigma_{00} - \epsilon \cos 2\varphi \sigma_{1-1} - 2\sqrt{\epsilon(1+\epsilon)} \cos \varphi \operatorname{Re} \sigma_{10} \right], \quad (30)$$

$$\left( \frac{d^6\sigma}{dE'd\Omega_e d\Omega_\pi} \right)_{P_e} - \left( \frac{d^6\sigma}{dE'd\Omega_e d\Omega_\pi} \right) = \Gamma_t \frac{2P_e}{m_e} \sqrt{\epsilon(1-\epsilon)} \sin \varphi \operatorname{Im} \sigma_{10}, \quad (31)$$

$$\sigma_{11} = \frac{1}{4Wk^2} (2A_+ + g^2 \sin^2 \theta C), \quad (32)$$

$$\sigma_{1-1} = \frac{1}{4Wk^2} (-g^2 \sin^2 \theta C), \quad (33)$$

$$\sigma_{00} = \frac{1}{4Wk^2} \left[ 2A_+ + \frac{2(k_0 g \cos \theta - k g_0)^2}{m_\pi^2} C + \frac{2k^2 (P_0 + k_0)^2}{m_\pi^2} B + \frac{4(k_0 g \cos \theta - k g_0) R (P_0 + k_0)}{m_\pi^2} F_+ \right], \quad (34)$$

$$\operatorname{Re} \sigma_{10} = \frac{1}{4Wk^2} \left[ -\frac{\sqrt{2} g \sin \theta (k_0 g \cos \theta - k g_0)}{m_\pi} C - \frac{\sqrt{2} g \sin \theta R (P_0 + k_0)}{m_\pi} F_+ \right], \quad (35)$$

$$\operatorname{Im} \sigma_{10} = \frac{1}{4Wk^2} \left[ \frac{\sqrt{2} k g \sin \theta (P_0 + k_0)}{m_\pi} F_- \right], \quad (36)$$

where

$$\Gamma_t = \frac{\alpha}{2\pi^2} \frac{E'}{E} \frac{K}{k_\mu^2} \frac{1}{1-\epsilon}, \quad (37)$$

$$K = \frac{1}{2M} (W^2 - M^2) = \frac{Wk^2}{M}. \quad (38)$$

$P_e$  is the polarization of electron in the direction of momentum in Laboratory system (L system).  $E$  and  $E'$  are initial and final electron energy in L system, respectively.  $d\Omega_e$  is the solid angle of the final electron in L system, and  $\epsilon$  is the usual transverse linear polarization parameter. In the above representation it should be noted that photon-vector meson coupling constant and factor  $m_\pi^2/(k_\mu^2 + m_\pi^2)$  are contained in the amplitude for the reaction " $\gamma + N \rightarrow \pi + N$  (or  $e + N \rightarrow e + \pi + N$ ).

Using the above representation, we make the following two kinds of approximation:

(i) Assuming that the invariant discontinuities are independent of  $k_\mu^2$ , we get the usual VMD relations as

$$\left(\frac{d^3\sigma}{d^3q}\right)_\perp^{\pi\pi} = \frac{g}{k} g_{\gamma\pi}^2 (\rho_{11} \pm \rho_{1-1}) \left(\frac{d^3\sigma}{d^3k}\right)^{\pi\nu} \quad (39)$$

We know that these relations are correct within a factor of 2, however we may even say that the usual VMD relations are not consistent with experiment.

(ii) In the region  $|k_\mu^2| \lesssim m_\rho^2$ , we expand the Lorentz invariant amplitudes up to the first order in  $k_\mu^2$ ;

$$\begin{aligned} A_+ &= A_+^{(0)} + k_\mu^2 A_+^{(1)}, \\ B &= B^{(0)} + k_\mu^2 B^{(1)}, \quad \text{etc.} \end{aligned} \quad (40)$$

where  $A_+^{(0)}$ ,  $A_+^{(1)}$ , ... are  $k_\mu^2$ -independent, and we assume the higher discontinuities are zero (Eqs. (41), (42) and (43) are not altered by this assumption). Requiring that the gauge conditions are satisfied for each power of  $k_\mu^2$ , we get the following three additional subsidiary conditions among the ten  $k_\mu^2$ -independent amplitudes;

$$A_+^{(0)} = \frac{1}{4} (t - \mu^2)^2 C^{(1)} + \frac{1}{4} (u - M^2)^2 B^{(1)} + \frac{1}{2} (t - \mu^2)(u - M^2) F_+^{(1)}, \quad (41)$$

$$B^{(0)} = - \frac{t - \mu^2}{u - M^2} F_+^{(0)}, \quad (42)$$

$$C^{(0)} = - \frac{u - M^2}{t - \mu^2} F_+^{(0)}. \quad (43)$$

Now the number of  $k_\mu^2$ -independent amplitudes is smaller than that of the experimentally observable quantities.

### 3. Comparison With the Experimental Results

When the initial nucleon and lepton are unpolarized and we do not measure the polarization of the final nucleon, it is enough to take the eight  $k_\mu^2$ -independent amplitudes  $A_+^{(0)}$ ,  $A_+^{(1)}$ ,  $B^{(0)}$ ,  $B^{(1)}$ ,  $C^{(0)}$ ,  $C^{(1)}$ ,  $F_+^{(0)}$  and  $F_+^{(1)}$ . We have three subsidiary relations (41), (42) and (43) between them, so we have only five  $k_\mu^2$ -independent amplitudes. For fixed  $s$  and  $t$ , we have the following experimentally observable quantities;

$$(\gamma N \rightarrow \pi N): \left(\frac{d^3\sigma}{d^3q}\right)_\perp^{\gamma\pi}, \quad \left(\frac{d^3\sigma}{d^3q}\right)_\parallel^{\gamma\pi}, \quad (44)$$

$$(\pi N \rightarrow \nu N): \rho_{11} \left(\frac{d^3\sigma}{d^3k}\right)^{\pi\nu}, \quad \rho_{00} \left(\frac{d^3\sigma}{d^3k}\right)^{\pi\nu}, \quad \rho_{1-1} \left(\frac{d^3\sigma}{d^3k}\right)^{\pi\nu}, \quad \text{Re } \rho_{10} \left(\frac{d^3\sigma}{d^3k}\right)^{\pi\nu}, \quad (45)$$

$$(eN \rightarrow e\pi N): \sigma_{11}, \quad \sigma_{00}, \quad \sigma_{1-1}, \quad \text{Re } \sigma_{10} \quad \text{for each } k_\mu^2. \quad (46)$$

Using the following  $\gamma$ - $\nu$  coupling constant<sup>7)</sup>

$$\frac{\gamma_\nu^2}{4\pi} = \frac{1}{16\pi} \frac{e^2}{g^2} = 0.64 \pm 0.05, \quad (47)$$

we can fit the six observable quantities,  $\left(\frac{d^3\sigma}{d^3q}\right)_\perp^{\gamma\pi}$ ,  $\left(\frac{d^3\sigma}{d^3q}\right)_\parallel^{\gamma\pi}$ ,

$$\rho_{11} \left(\frac{d^3\sigma}{d^3k}\right)^{\pi\nu}, \quad \rho_{00} \left(\frac{d^3\sigma}{d^3k}\right)^{\pi\nu}, \quad \rho_{1-1} \left(\frac{d^3\sigma}{d^3k}\right)^{\pi\nu} \quad \text{and} \quad \text{Re } \rho_{10} \left(\frac{d^3\sigma}{d^3k}\right)^{\pi\nu}$$

by adjusting the five independent amplitudes  $A_+^{(1)}$ ,  $B^{(1)}$ ,  $C^{(1)}$ ,  $F_+^{(0)}$  and  $F_+^{(1)}$ . The fits to the data are shown on Figs.1 to 7. The fitted amplitudes  $A_+^{(0)}$ ,  $A_+^{(1)}$ ,  $B^{(0)}$ ,  $B^{(1)}$ ,  $C^{(0)}$ ,  $C^{(1)}$ ,  $F_+^{(0)}$  and  $F_+^{(1)}$  are shown on Figs.8 to 11. For comparison we plot the prediction of usual VMD in Figs.6 and 7. This shows our fit is much better than that by the usual VMD, and is consistent with the experiment within errors. Also we can make a prediction for the pion electro-production cross section as in Fig.12.

From Fig.8 ~ 11, we may classify the amplitudes into two classes; the amplitudes A and C where the zeroth order component has the same magnitude and shape as the first order component, and the amplitudes B and  $F_+$  where the zeroth order component has much smaller magnitude compared with the first order

component. Anyway it is very remarkable that these amplitudes have quite a large  $k_\mu^2$ -dependency.

#### 4. Discussion

In this note we fit the six observable quantities on the  $\Upsilon N \rightarrow \pi N$  and  $\pi N \rightarrow \Upsilon N$  processes by using five  $k_\mu^2$ -independent amplitudes. The fit is quite satisfactory and this becomes very nice modification of the usual VMD. The most striking and remarkable results are that the amplitudes have quite a large  $k_\mu^2$ -dependency. This is a very unexpected result.

On the other hand, experimental indications recently have been found for at least more vector meson,  $\rho'(1600)$ . Many authors are trying to fit the photo processes considering an infinite series of vector mesons; this is called generalized vector meson dominance (GVMD).<sup>9)</sup>

If the GVMD is correct in our processes, the following quantities should have some relations with the  $k_\mu^2$ -dependency of the amplitudes:

$$\left[ \frac{1}{\gamma_{\rho'}} \sqrt{\left(\frac{d\sigma}{dk}\right)^{\pi\rho'}} + \frac{1}{\gamma_{\rho''}} \sqrt{\left(\frac{d\sigma}{dk}\right)^{\pi\rho''}} e^{i\varphi} + \dots \right] / \frac{1}{\gamma_\rho} \sqrt{\left(\frac{d\sigma}{dk}\right)^{\pi\rho}} \quad (48)$$

At present we do not have enough data in order to compare with GVMD.

We also calculated the pion electroproduction cross section. Our fit looks a little bit better than the usual VMD, in particular in the magnitude of the cross section. The increasing amount of data on pion electroproduction will be very interesting in order to check our new form of VMD.

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Figure Captions

- Fig.1,2,3 and 4: The  $\rho^0$  density-matrix elements in the helicity frame. The solid (dashed) curve is a fit with our predictions for  $\gamma_{\rho^0}^2/4\pi = 0.64$  (0.5). Experimental data are taken from F. Bulos et al.<sup>8)</sup>
- Fig.5: Differential cross section ( $d\sigma/dt$ ) for  $\pi^- p \rightarrow \rho^0 n$  at 15 GeV/c<sup>8)</sup> with our predictions (solid line).
- Fig.6 and 7: Differential cross sections for single-pion photoproduction<sup>8)</sup> with our prediction (solid curve). For comparison the usual predictions of VMD from  $\pi N \rightarrow \rho^0 N$  data are given (closed circle).
- Fig.8, 9, 10 and 11: Fitted Parameters used in our prediction. The solid (dashed) curve is for  $\gamma_{\rho^0}^2/4\pi = 0.64$  (0.5). (see text)
- Fig.12: Prediction for electroproduction. Data are taken from C. Driver et al.<sup>8)</sup> (for  $k_{\mu}^2 = + 0.26 \text{ GeV}^2$ ). For comparison the prediction by H. Fraas and D. Schildknecht is given (closed circle).

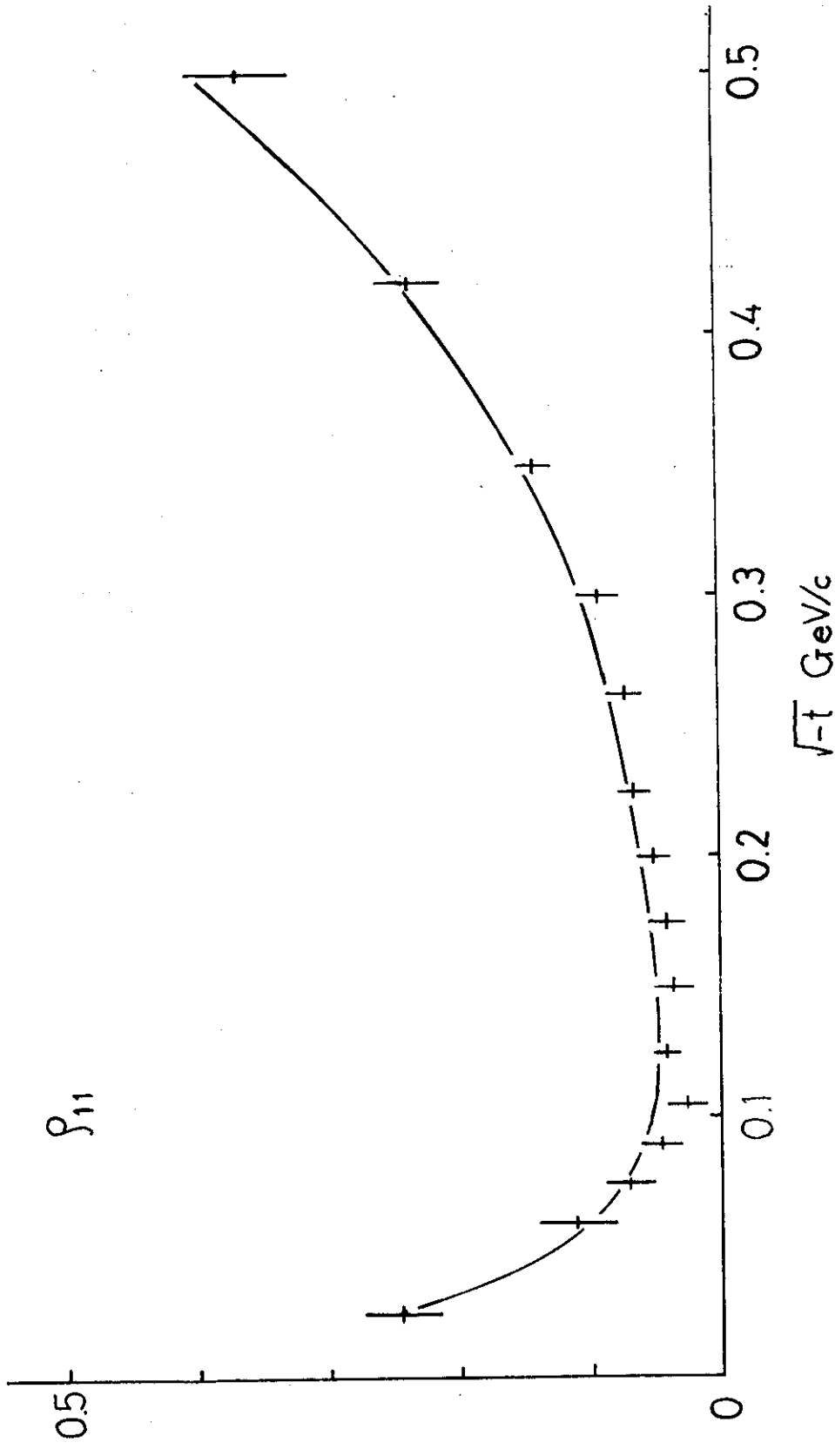


Fig.1

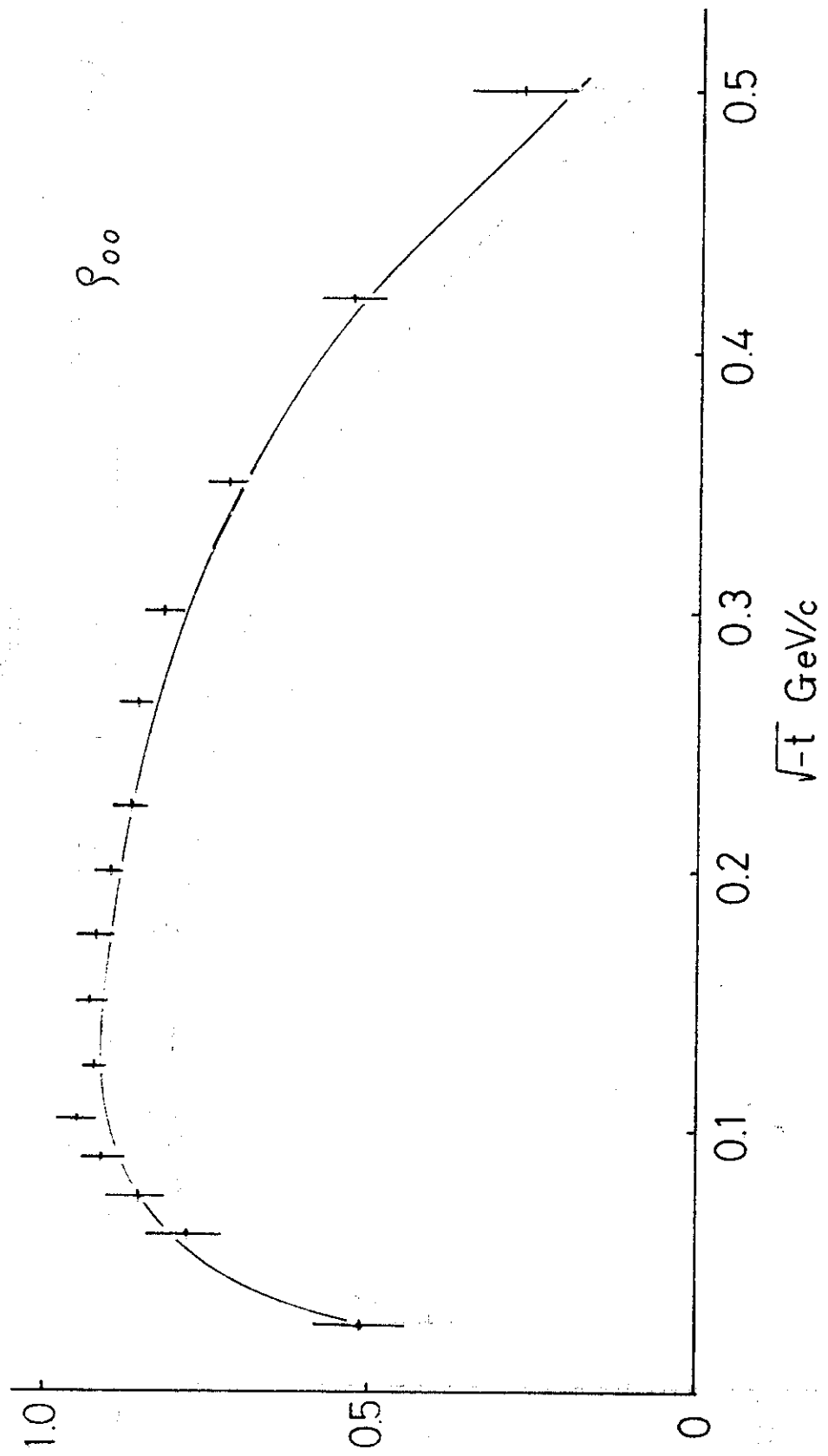


Fig.2



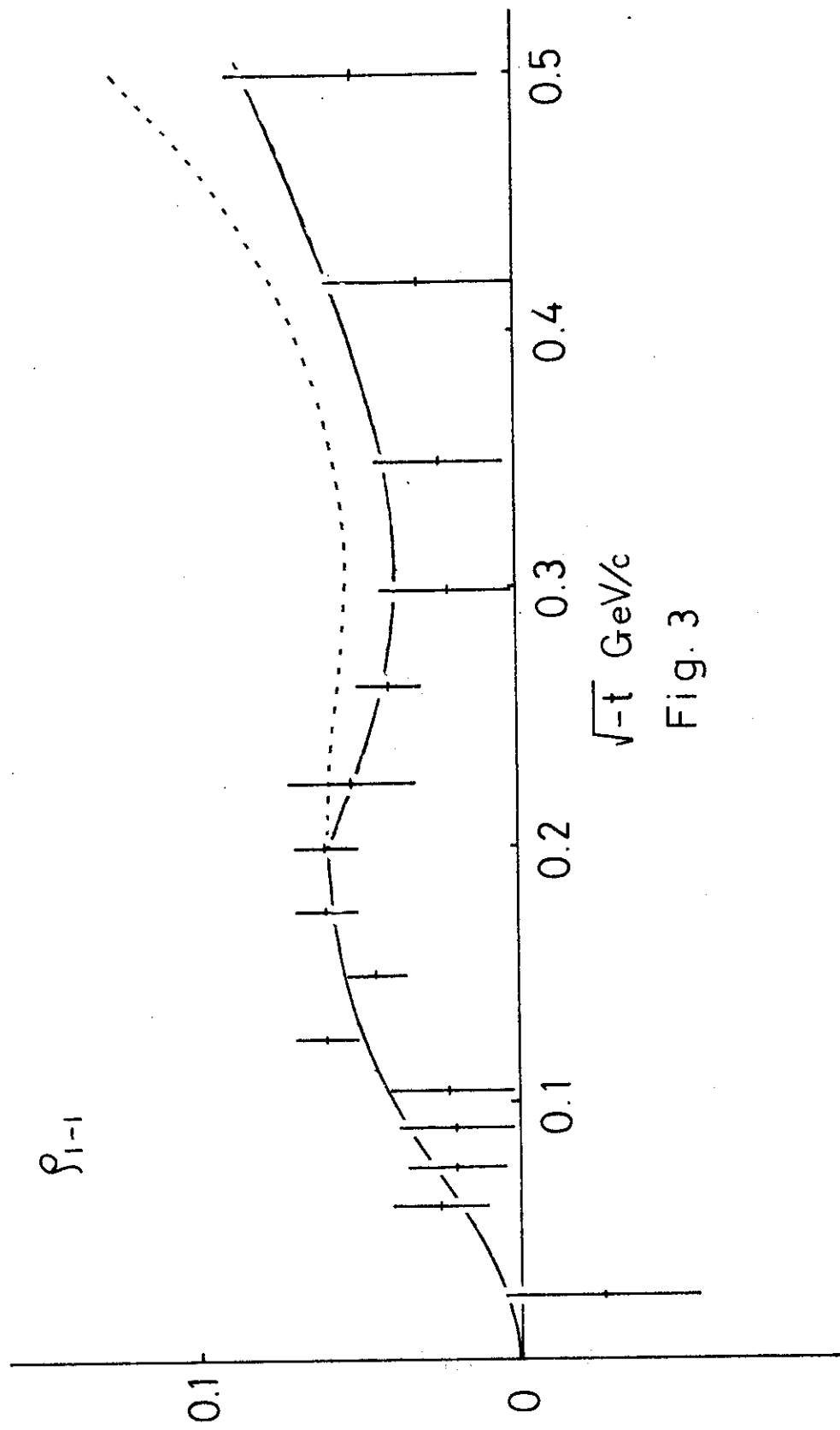


Fig. 3

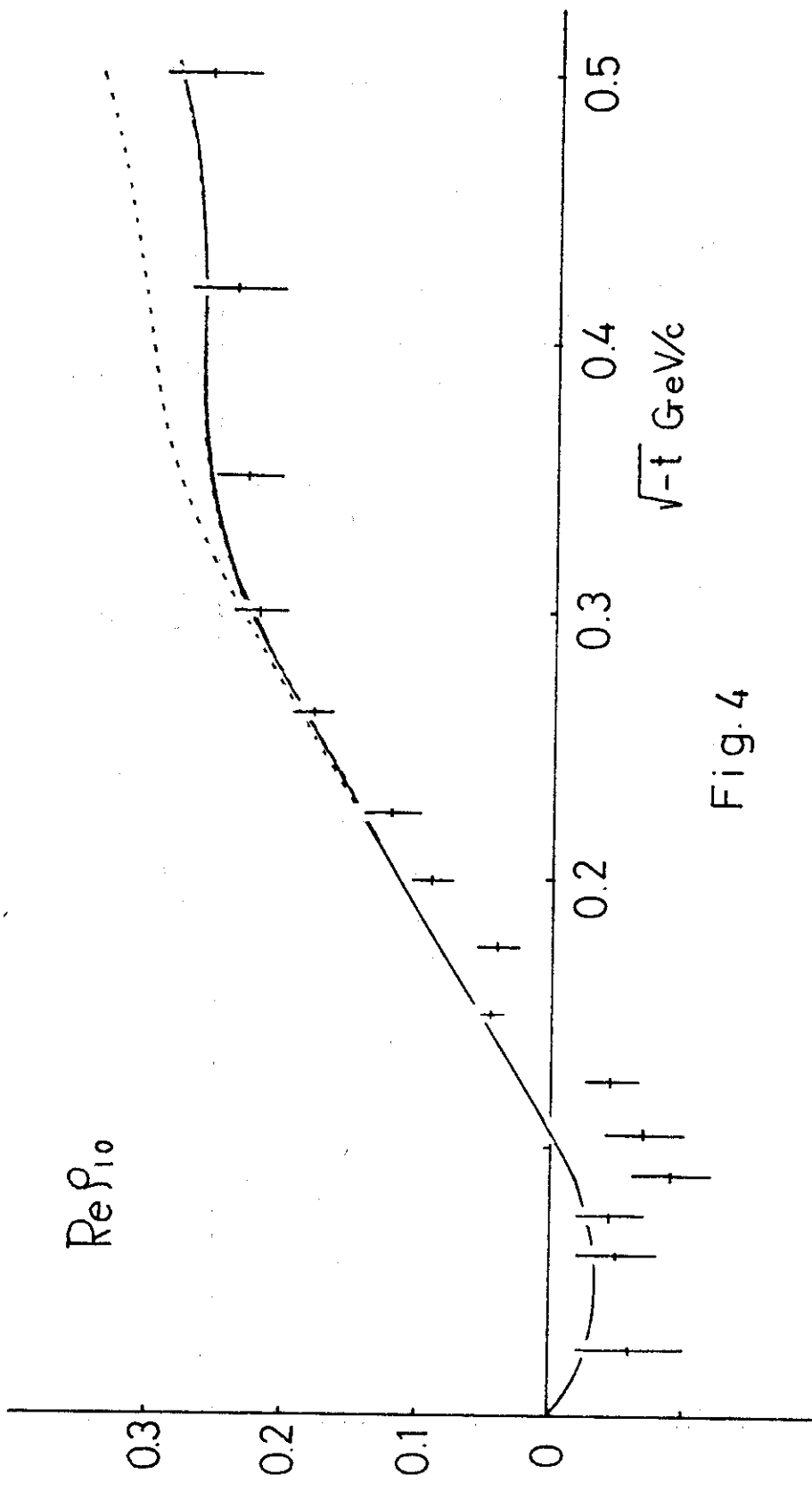


Fig. 4

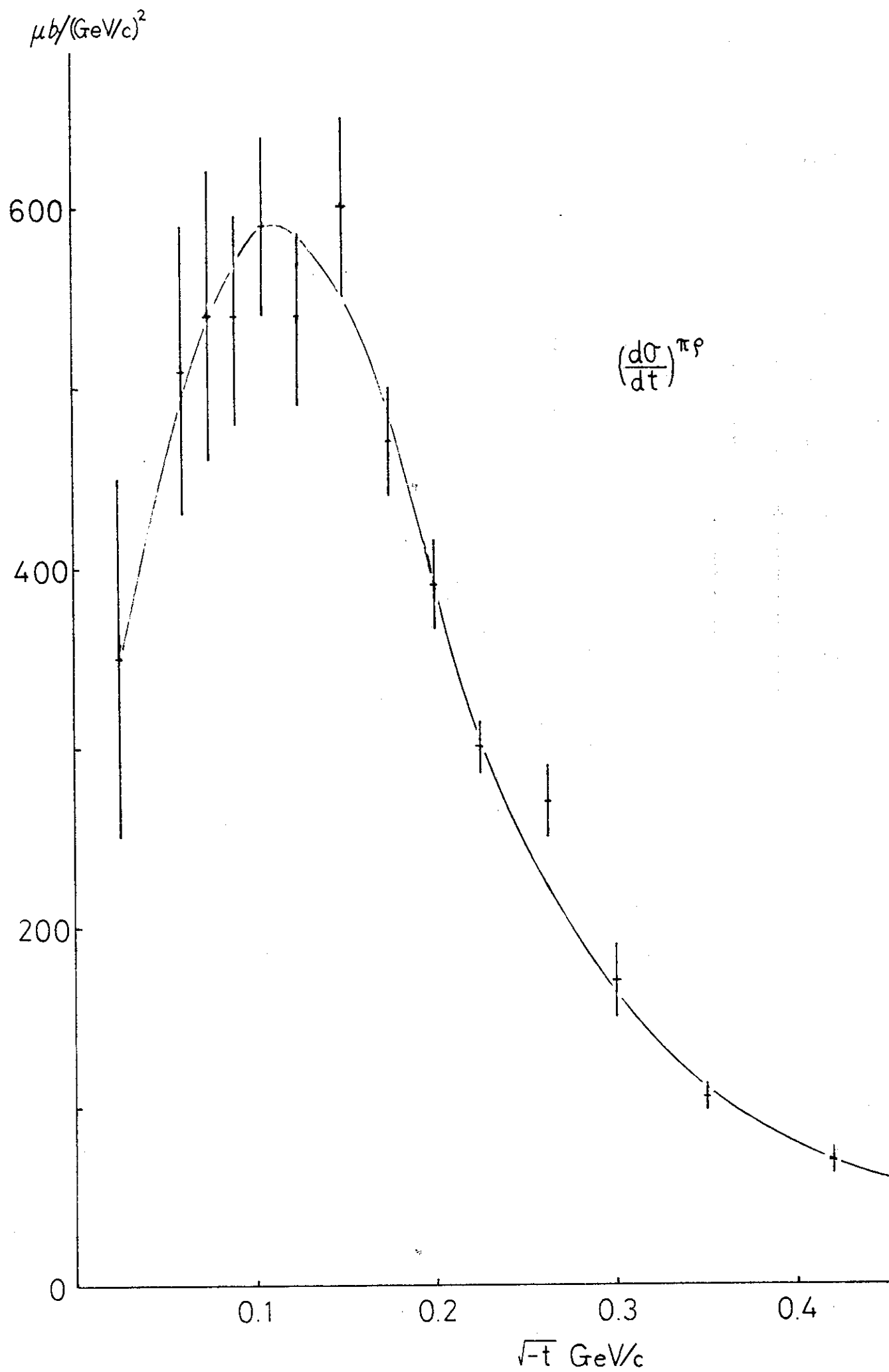


Fig.5

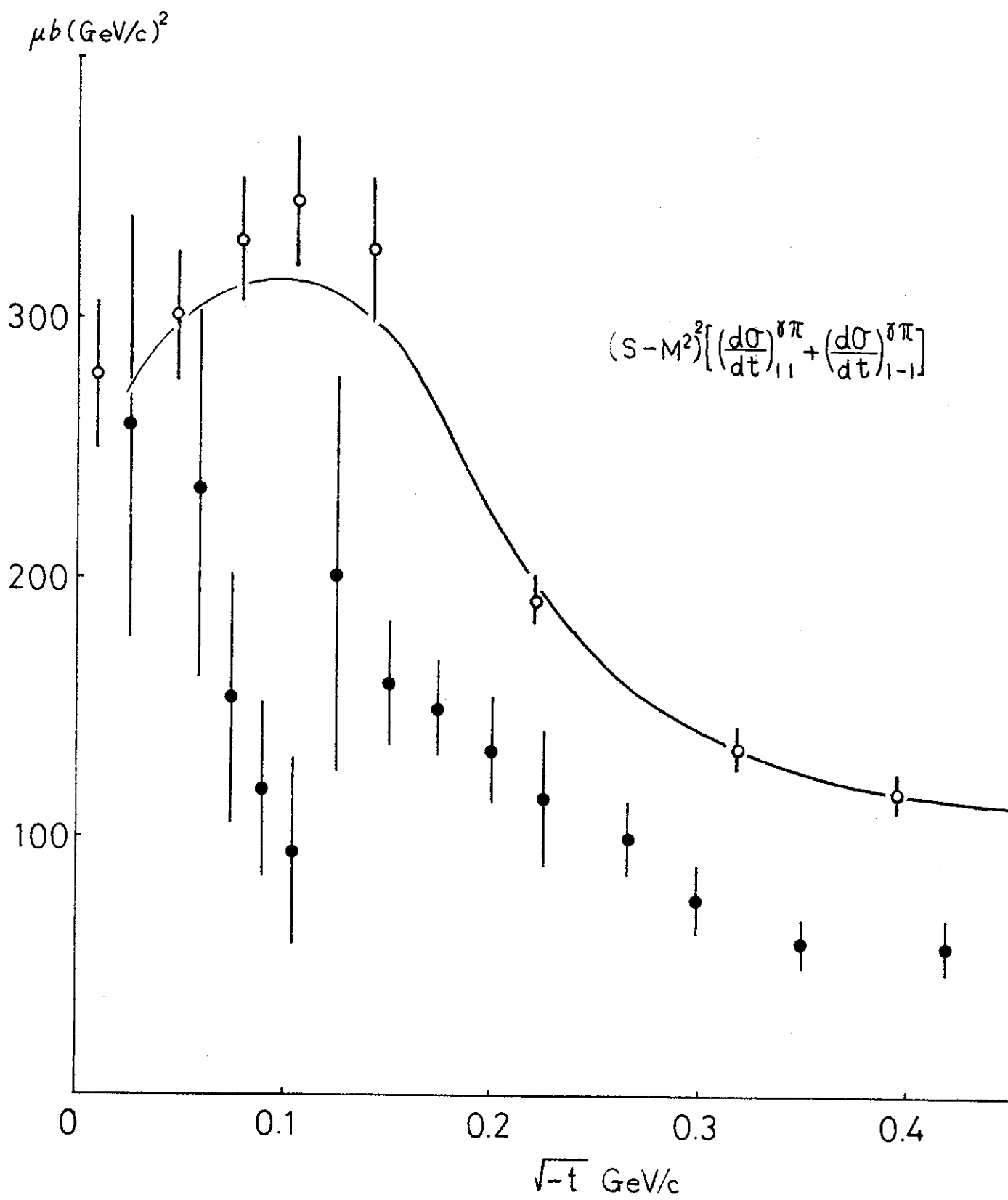


Fig.6

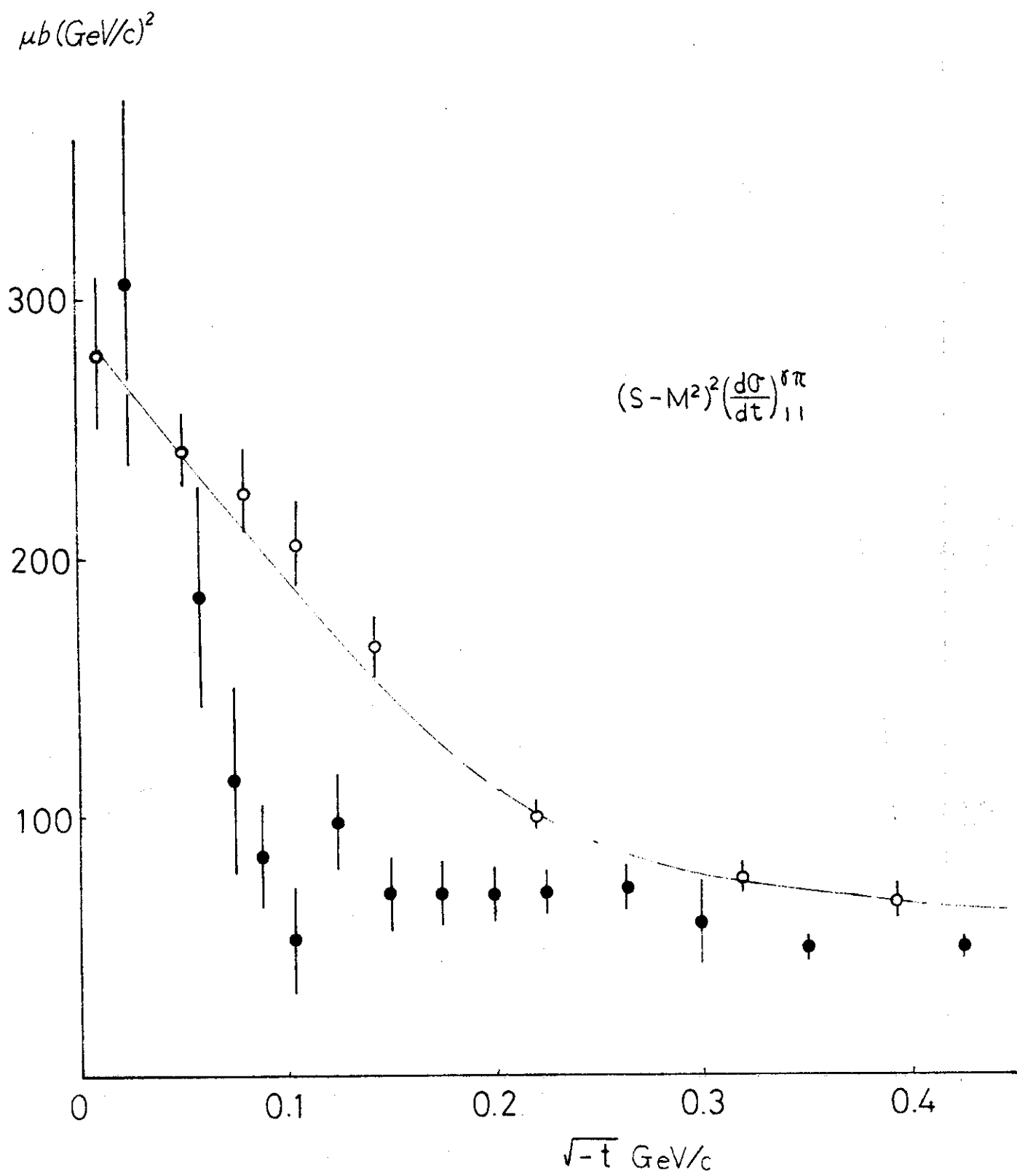


Fig. 7

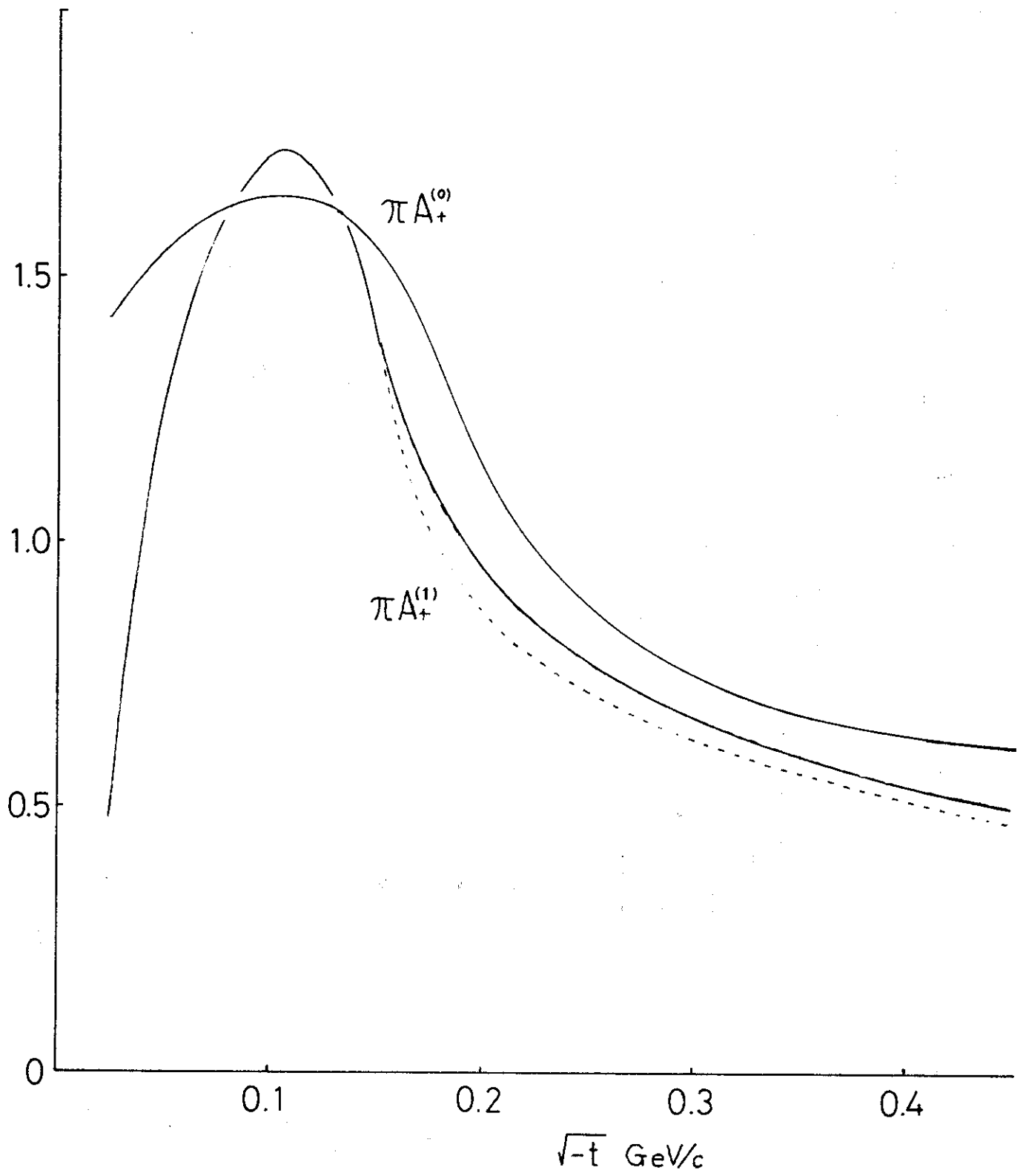


Fig.8

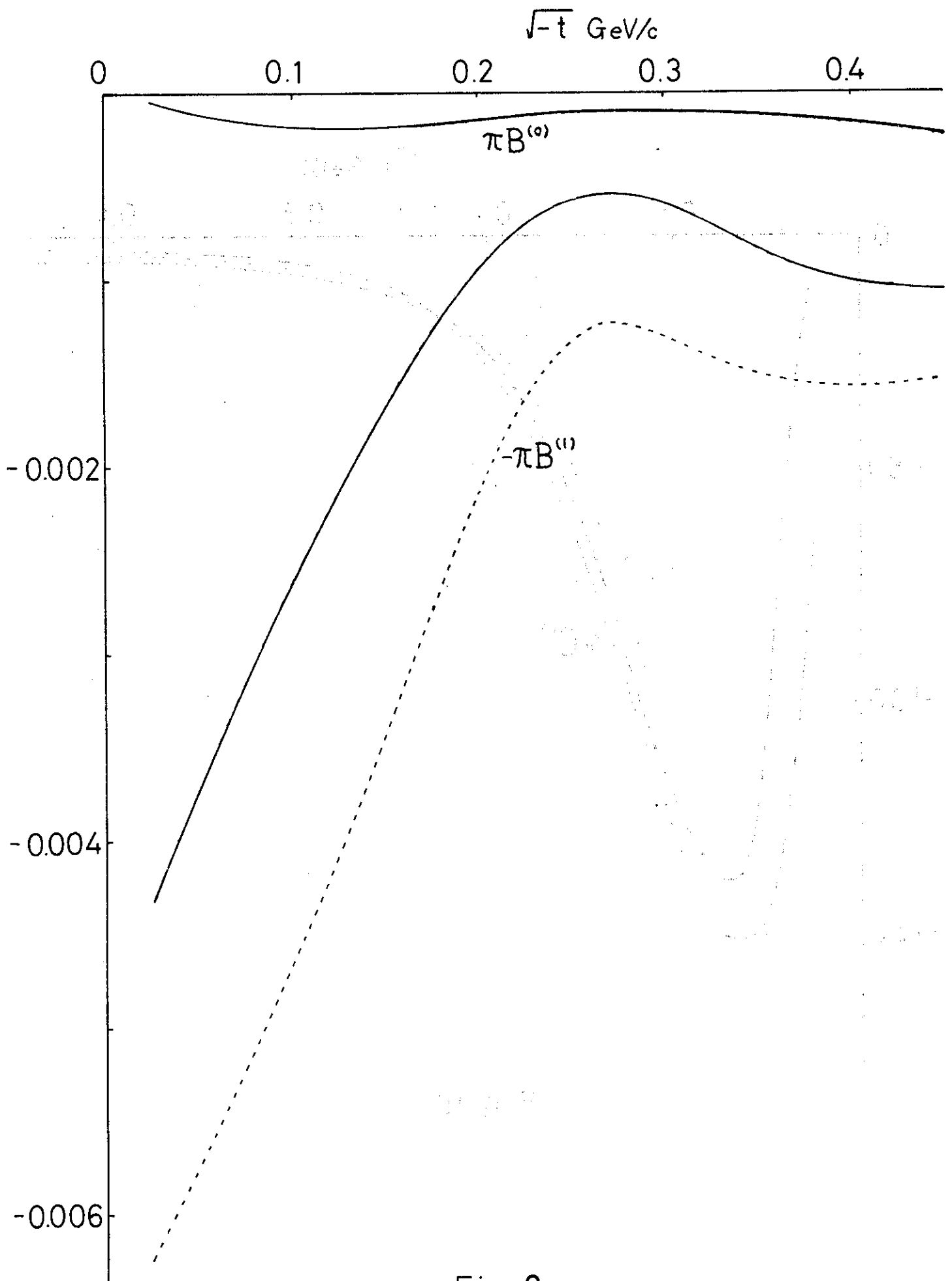


Fig. 9

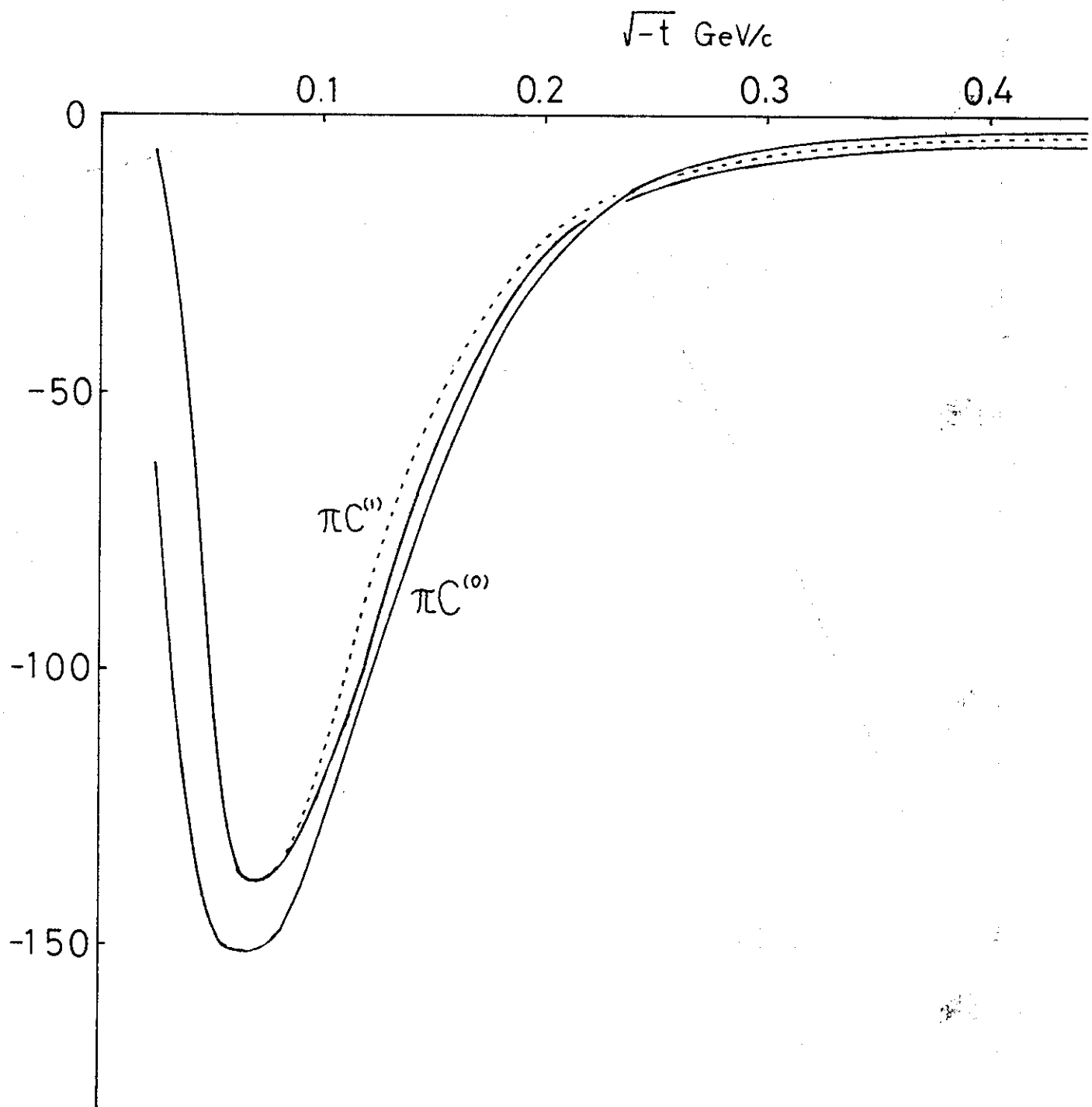


Fig. 10



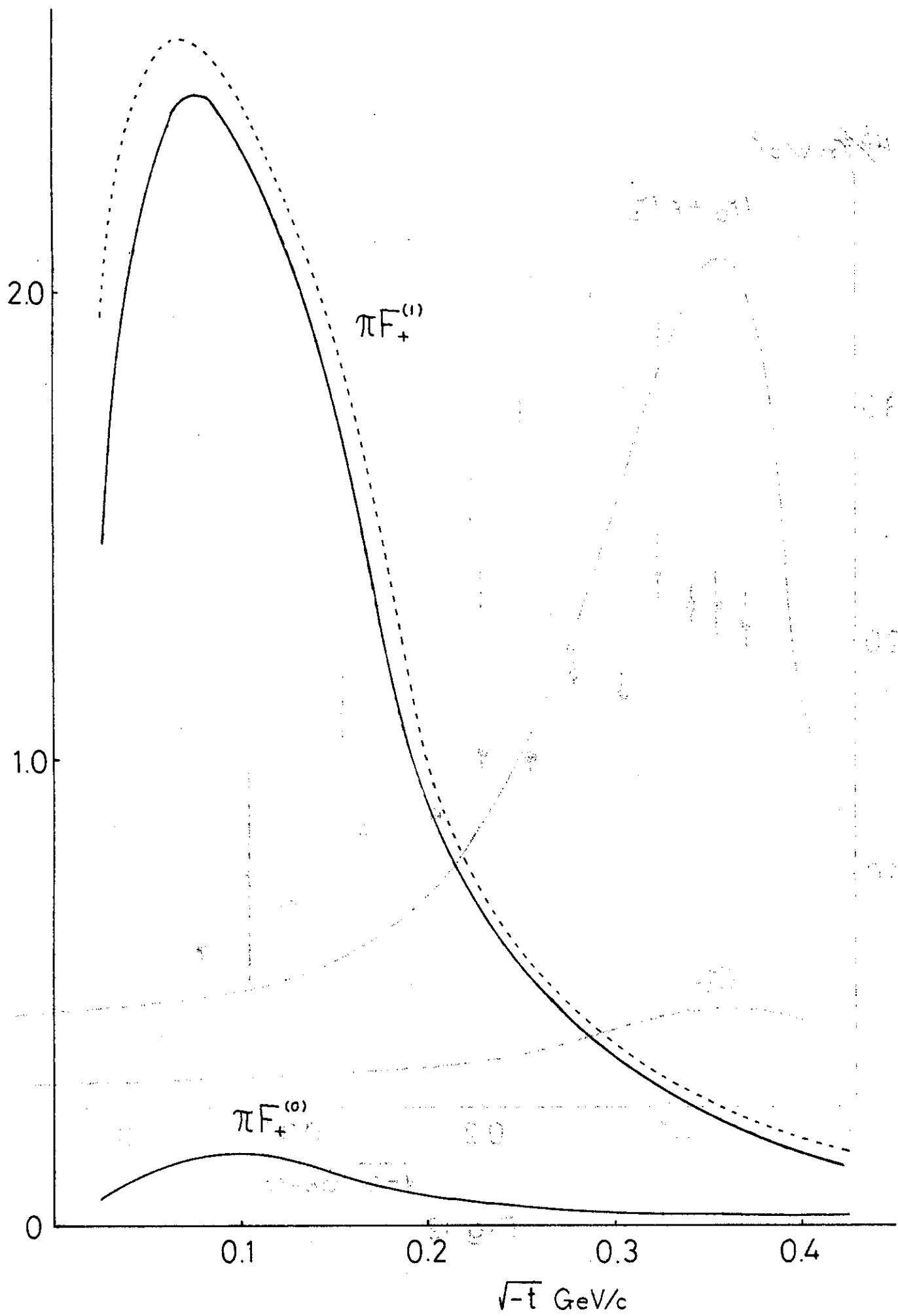


Fig.11

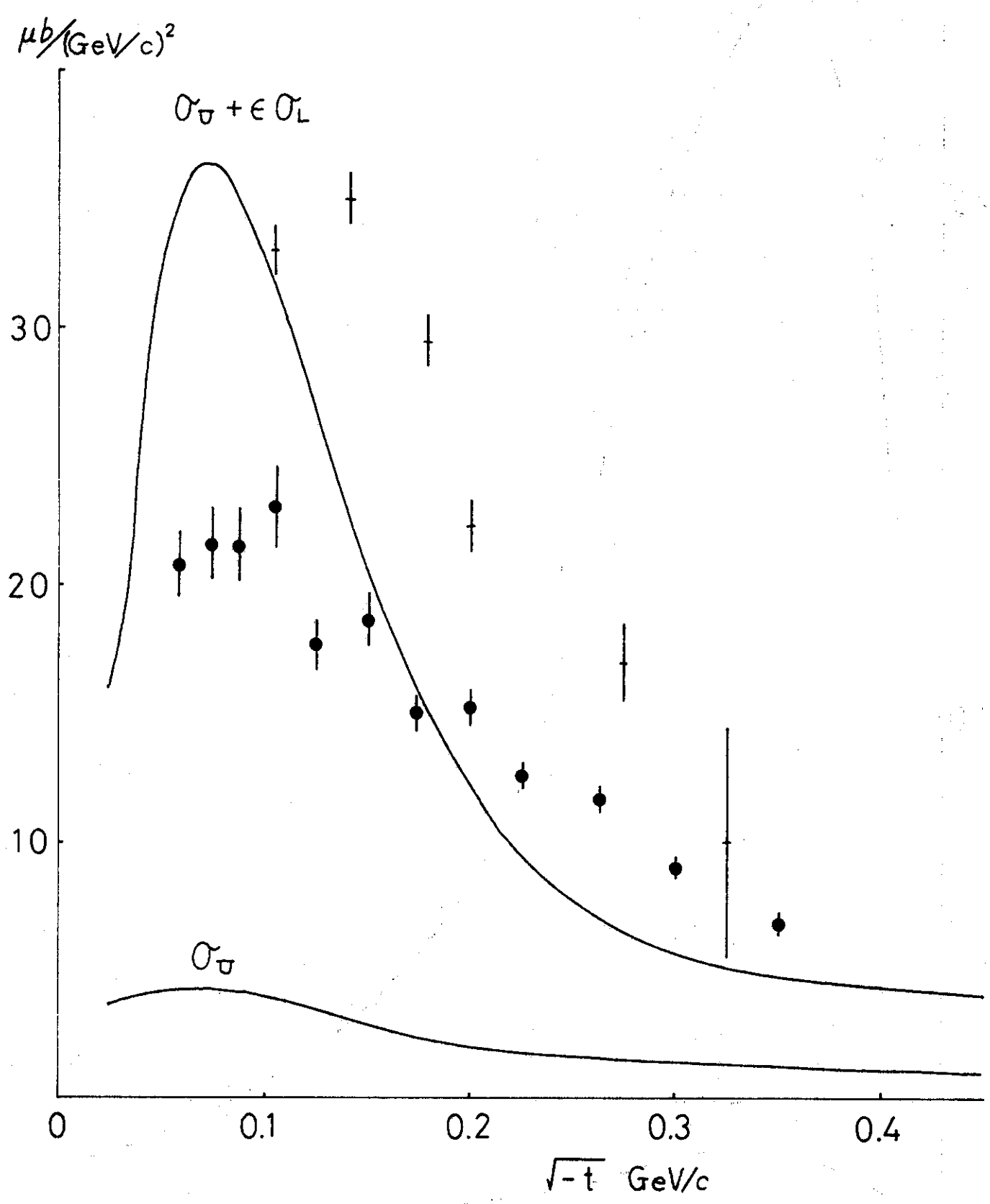


Fig.12