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Reaction  $\pi^+ p \rightarrow \rho^0 \Delta^{++}$  at 13.1 GeV/c\*

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The differential cross section and  $\rho$  density matrix elements for the reaction  $\pi^+ p \rightarrow \rho^0 \Delta^{++}$  at 13.1 GeV/c are presented. The data are interpreted in terms of an absorption model with conventional pion exchange. The transverse  $\rho^0$  production is compared with the predictions of vector dominance.

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The highly peripheral reaction  $\pi p \rightarrow \rho \Delta$  is of considerable importance in distinguishing between various exchange models. The result of this experiment and similar experiments at <sup>(1)</sup> 8 GeV/c or less suggest the above reaction is dominated by pion exchange. According to LeBellac, <sup>(2)</sup> if the above reaction is described by a model of conspiring Regge poles the pion contribution has a dip in the forward direction. This is unlike the  $np$  charge exchange reaction where conspiracy implies a forward peak. In contrast, most models with absorption effects have a forward peak structure. However, since the finite widths of the  $\rho$  and  $\Delta$  tend to smear out dips in the differential cross section, an energy of 8 GeV/c or greater is required to resolve the forward structure, as suggested by J. Donohue. <sup>(3)</sup>

We have analyzed the differential cross section and  $\rho$  density matrix for the reaction  $\pi^+ p \rightarrow \rho^0 \Delta^{++}$  at 13.1 GeV/c. The data were obtained from 230,000 pictures taken in the SLAC 82" bubble chamber. The four-prong events were measured on SMP's and analyzed by the local version of the TVGP-SQUAW data reduction and fitting programs. Some 10,000 events in the  $\pi^+ \pi^+ \pi^- p$  final state were fit; after correction for background, the  $\rho^0 \Delta^{++}$  cross section was found to be  $.17 \pm .02$  millibarns, normalized to the total  $\pi^+ \pi^+ \pi^- p$  cross section of  $1.23 \pm .04$  millibarns. The  $\rho$  and  $\Delta$  widths are observed to be  $\Gamma_\rho = \Gamma_\Delta = .12$  GeV. For the subsequent analysis, the  $\rho^0 \Delta^{++}$  region is defined by  $M_{\pi^+ \pi^+} = .765 \pm .1$  GeV and  $M_{\pi^+ p} = 1.236 \pm .1$  GeV, yielding a sample of 1037 events. The distribution of events in  $|t'|$  is presented in Fig. 1, in which the two dotted lines correspond to a coarse representation of the data by an exponential,  $N(t') \sim e^{B_1 t'}$ , where  $B_1$  and  $B_2$  are given by 20. and  $3.8$  (GeV/c)<sup>-2</sup> respectively (very close to the values 19.1 and 3.2 (GeV/c)<sup>-2</sup> quoted in the 8 GeV/c experiment); <sup>(4)</sup>  $t' = t - t_{\min}$ ,

and  $t_{\min}$  is the minimum momentum transfer for a given event. A rise in the forward direction,  $|t'| < \mu^2$  is clearly exhibited in the inset to Fig. 1. This distribution is described quite nicely in terms of a pion exchange model with absorption, and clearly is not consistent with an M=1 pion conspiracy.

The detailed comparisons with models, given below, use only those events with  $|t'| < 0.2 \text{ (GeV/c)}^2$ . Beam momentum spread and resonance widths cause  $|t_{\min}|$  to vary from .008 to .028  $\text{(GeV/c)}^2$ ; but 72% of the events have  $|t_{\min}|$  between .012 and .02  $\text{(GeV/c)}^2$  with an average of .016  $\text{(GeV/c)}^2$ . By comparison the average  $|t_{\min}|$  in the 8 GeV/c experiment was .028  $\text{(GeV/c)}^2$ .

The two prominent features of the data are a strong forward peak of width approximately  $\mu^2$  in the differential cross section as a function of  $|t'|$  with a secondary break at  $|t'| \approx .15 \text{ GeV/c}^2$  (Fig. 1), and a large value of  $(\rho_{00} - \rho_{11})$  in the forward direction (Fig. 2). The values of  $\text{Re } \rho_{10}$  and  $\rho_{1-1}$  are consistent with zero for  $|t'| < .2 \text{ (GeV/c)}^2$ . The observed fore-aft asymmetry in the Jackson angle distribution is  $.36 \pm .04$ , indicating some s-wave background. If the value of  $\rho_{11}(t')$  is estimated from the absorption model given below and this contribution subtracted from the constant part of  $\frac{d\sigma(t')}{d\cos\theta_J}$ , the s-wave background is less than 10% for  $|t'| < .04$  and less than 5% thereafter. Neglecting the s-wave contribution, the fitted values of  $\rho_{00}$  are shown in Fig. 4, along with the data from the 8 GeV/c experiment, <sup>(5)</sup> where the dotted lines represent calculations based on the absorption model, at 13 and 8 GeV/c.

An absorption model is presented which fits all of the above data; the sharp forward peak is given by a pole term, the secondary break by amplitudes which vanish in the forward direction but rise smoothly to maxima at  $|t'| \sim .1 \text{ (GeV/c)}^2$ . The absorption terms are relatively small in the forward direction but tend to give large contributions for larger  $|t'|$ .

The nonhelicity flip cross section is consistent with a very different model containing interference between pion and  $A_1$  meson Regge poles without absorption.

Standard Regge analysis begins with the t-channel amplitudes for the reaction  $\bar{\Delta}(\lambda')N(\lambda) \rightarrow \rho(\mu)\pi$  which are denoted by  $f_{\lambda'\lambda\mu}$ , where  $\lambda'$ ,  $\lambda$  and  $\mu$  are the helicities of the  $\Delta$ ,  $N$ , and  $\rho$ , respectively. These amplitudes satisfy the kinematic constraints for values of  $t$  corresponding to psuedothresholds, the one of interest here being  $(M_\Delta - M_N)^2 = 4\mu^2$ . The Regge pole contribution is given by

$$f_{\lambda'\lambda\mu} \sim \frac{\pi}{2} \alpha' \frac{\gamma_{\lambda'\lambda\mu}}{\sin \frac{\pi}{2} \alpha} e^{-\frac{i}{2} \pi \alpha} (s/s_0)^\alpha$$

where  $\alpha(t)$  is the Regge trajectory and  $\rho(t)$  the residue. The existence of a forward peak and the large value of  $\rho_{00}$  prove in a model independent way that  $f_{\frac{1}{2}\frac{1}{2}0}$  dominates in the forward direction. We start with

$\gamma_{\frac{1}{2}\frac{1}{2}0} = 4g_\rho g_\Delta (p_\pi \cdot \epsilon) (\bar{U}_\nu U_N^\nu)$  suggested by the Feynman diagram for pion exchange, where  $U_\nu$ ,  $U$  and  $\epsilon$  are the spin 3/2, 1/2 and 1 wave functions, respectively, and the couplings  $g_\rho$ ,  $g_\Delta$  are related to the widths in the usual way.<sup>(6)</sup> This is the only coupling for a physical pion and it automatically satisfies the psuedothreshold constraints. This term alone is essentially the model used by Haber et al.,<sup>(7)</sup> and fits the forward part of the cross section reasonably well, but not the density matrix elements. Absorption is introduced following Henyey, Kane, Pumplin and Ross,<sup>(8)</sup> whose procedure is similar to that of Gottfried and Jackson,<sup>(9)</sup> but simpler to use. The reaction amplitudes with absorption are calculated in the s channel, where  $F_{\lambda'\lambda\mu}$  is the amplitude for  $\pi N(\lambda) \rightarrow \rho(\mu)\Delta(\lambda')$ . The model gives

$$F(t') = F^{\pi}(t') - \frac{\lambda\sigma}{8\pi} \int_{-\infty}^0 dy' e^{\frac{1}{2}A(t'+y')} I_n(A\sqrt{t'y'}) F^{\pi}(y')$$

where the helicity indices have been suppressed;  $F^{\pi}$  is the s-channel amplitude corresponding to  $f_{\frac{1}{2}\frac{1}{2}0}$  in the t-channel,  $\sigma$  and  $A$  are parameters from elastic  $\pi N$  scattering,  $I_n$  the modified Bessel function, and  $n$  the net helicity flip. The factor  $\lambda$  is introduced to represent contributions from processes other than elastic scattering or as a measure of elastic  $\rho\Delta$  scattering. Henyey et al. find  $1.5 < \lambda < 2.0$ . The fall off with  $|t'|$  of the density matrix element  $\rho_{00}-\rho_{11}$  requires  $\lambda = 1.6 \pm .2$  as shown in (Fig. 2), which is in good agreement with the result of Henyey et al. With  $\lambda = 1.6$ , the values  $A = 4 \text{ (GeV/c)}^{-2}$ , and  $\sigma = 24.5 \text{ mb}$  from elastic scattering and the accepted values of  $s_0 = 1.0 \text{ (GeV/c)}^2$  and  $\alpha'_{\pi} = 1.0 \text{ (GeV/c)}^{-2}$  there are no free parameters. The curve in Fig. 3 corresponds to these values and yields an 85% confidence level for the fit.<sup>(10)</sup> The fit is not very sensitive to variations of the parameters within the range  $1.4 < \lambda < 1.8$ ,  $.6 < s_0 < 1.0 \text{ (GeV/c)}^2$ , and  $.8 < \alpha' < 1.2 \text{ (GeV/c)}^{-2}$ .

An alternative consideration is the model<sup>9</sup> of Arbab and Brower,<sup>(1)</sup> with strong interference between the  $\pi$  and  $A_1$ . Although the pion contribution vanishes at  $t = 0$ ,  $f_{\frac{1}{2}\frac{1}{2}0}$  is non-zero because of strong  $A_1$  contributions. This model requires a strong decrease of all residues with  $t$  in addition to the  $(s/s_0)^{\alpha}$  term. Also, since  $f_{\frac{1}{2}\frac{1}{2}0}$  does not satisfy the pseudothreshold constraint by itself, the two "nonsense" amplitudes  $f_{3/2\frac{1}{2}0}$  and  $f_{\frac{1}{2}-\frac{1}{2}0}$  are needed. The results are interpreted in terms of  $\rho_{00} \frac{d\sigma}{d|t'|}$ , where a smooth interpolation of the data was used for  $\rho_{00}$ . With  $s_0 = 1 \text{ (GeV/c)}^2$  and  $\alpha'_{\pi} = 1.2 \text{ (GeV/c)}^{-2}$ , this model fits the data reasonably well (Fig. 5).

Both calculations agree with the 8 GeV/c data when evaluated at that energy. (12)

A sum rule derived from vector dominance arguments which relates the cross section for  $\gamma p \rightarrow \pi^{\pm} \Delta$  to the cross section of  $\pi p \rightarrow \rho \Delta$ , has been proposed recently by Dar; (13) specifically

$$\frac{d\sigma}{dt} (\gamma p \rightarrow \pi^{-} \Delta) + \frac{d\sigma}{dt} (\gamma n \rightarrow \pi^{+} \Delta) \approx g_{\gamma}^2 \frac{d\sigma}{dt} (\pi^{+} p \rightarrow \rho_{tr}^{\circ} \Delta)$$

where  $\omega$  and  $\phi$  contributions have been ignored. With

$$\frac{d\sigma}{dt} (\pi^{+} p \rightarrow \rho_{tr}^{\circ} \Delta) = 2\rho_{11}^h \frac{d\sigma}{dt} (\pi^{+} p \rightarrow \rho^{\circ} \Delta)$$

where  $\rho_{11}^h$  is the density matrix element in the helicity frame and  $g_{\rho\gamma}^2 = 4.6 \times 10^{-3}$ , the distribution of  $s^2 g_{\rho\gamma}^2 2\rho_{11}^h \frac{d\sigma}{d|t|}$  is shown in Fig. 6.

From lower energy  $\pi^{+} p \rightarrow \rho \Delta, \omega \Delta$  experiments and the data for the process  $\gamma p \rightarrow \pi^{-} \Delta$ , comparison with vector dominance relations is made and the ratio  $R = \frac{d\sigma}{dt} (\gamma n \rightarrow \pi^{+} \Delta) / \frac{d\sigma}{dt} (\gamma p \rightarrow \pi^{-} \Delta)$  is predicted. (13) The curve shown in Fig. 6 is a drawn interpolation of the cross section  $(1+R)s^2 \frac{d\sigma}{dt} (\gamma p \rightarrow \pi^{-} \Delta)$  from Dar. (13) The rather good agreement of the data with the curve may be somewhat fortuitous because of the imprecise definition of the  $\rho_{\Delta}^{\circ++}$  cross section. However the slopes agree quite well. The 13.1 GeV/c data is in excellent agreement with the data at 8 GeV/c.

In conclusion, the  $|t'|$  distribution of the reaction  $\pi^{+} p \rightarrow \rho_{\Delta}^{\circ++}$  exhibits a peak for  $|t'| \leq \mu^2$  superimposed upon an exponential decrease, where the exponent is  $\sim 20 (\text{GeV}/c)^{-2}$  for  $|t'| \leq .15$  and  $\sim 3 (\text{GeV}/c)^{-2}$  for  $.15 < |t'| < 1.$ , the value of  $\rho_{00}$  is large ( $\approx .9$ ) in the forward

direction and decreases to  $\approx .5$  at  $|t'| = .17 \text{ (GeV/c)}^2$ . These facts are described well by the model of Henyey et al. with conventional pion exchange plus absorption. The pion pole term does not vanish at  $t=0$  and is evasive in the sense that no conspiring relation between Regge trajectories is needed. The alternative model of Arbab and Brower with conspiring  $\pi$  and  $A_1$  exchange terms gives an adequate description of  $\rho_{00} \frac{d\sigma}{d|t'|}$ .

There is good agreement between the relation of transverse  $\rho$  production to  $\pi\Delta$  photoproduction rates given by vector dominance.

One of us (FTM) would like to acknowledge the contribution of Professor Gordon Kane concerning the interpretation of the absorption model.

## FIGURE CAPTIONS

Fig. 1.(a) Differential cross section as a function of  $|t'|$  for  $\pi^+ p \rightarrow \rho^0 \Delta^{++}$  at 13.1 GeV/c. The lines correspond to slopes of 20 and 3.8 (GeV/c)<sup>-2</sup>.

(b) Same as (a); but for small  $|t'|$ ; the line has a slope of 20 (GeV/c)<sup>-2</sup>.

Fig. 2. Rho density matrix element as a function of  $|t'|$  in the Jackson frame for  $\pi^+ p \rightarrow \rho^0 \Delta^{++}$  at 13.1 GeV/c; the curves are based on the model of Henyey et al.; <sup>(6)</sup>  $\lambda$  is a parameter which modifies the absorptive contribution.

Fig. 3.(a) Differential cross section as a function of  $|t'| = |t - t_{\min}|$  for the reaction  $\pi^+ p \rightarrow \rho^0 \Delta^{++}$  at 13.1 GeV/c. The curve is a calculation based on the model of Henyey et al. <sup>(6)</sup> (Not normalized to the data).

(b) Same as (a), but enlarged for the region  $0 < |t'| < .1$ .

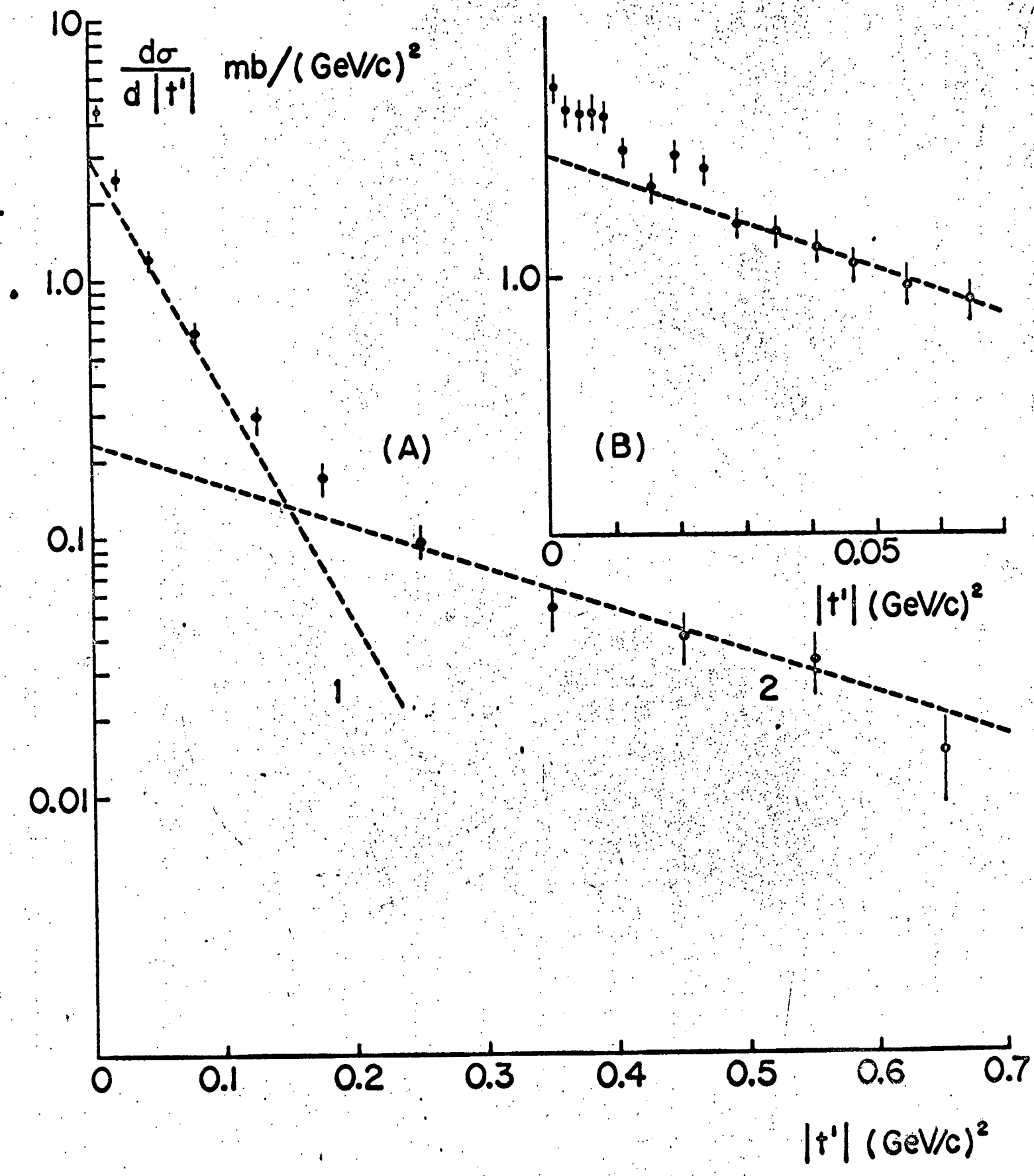
Fig. 4.  $\rho_{00}(|t'|)$  in the Jackson frame from data at 13.1 GeV/c and 8 GeV/c. The dotted lines are obtained from the absorption model at these energies, the upper line corresponding to the higher energy.

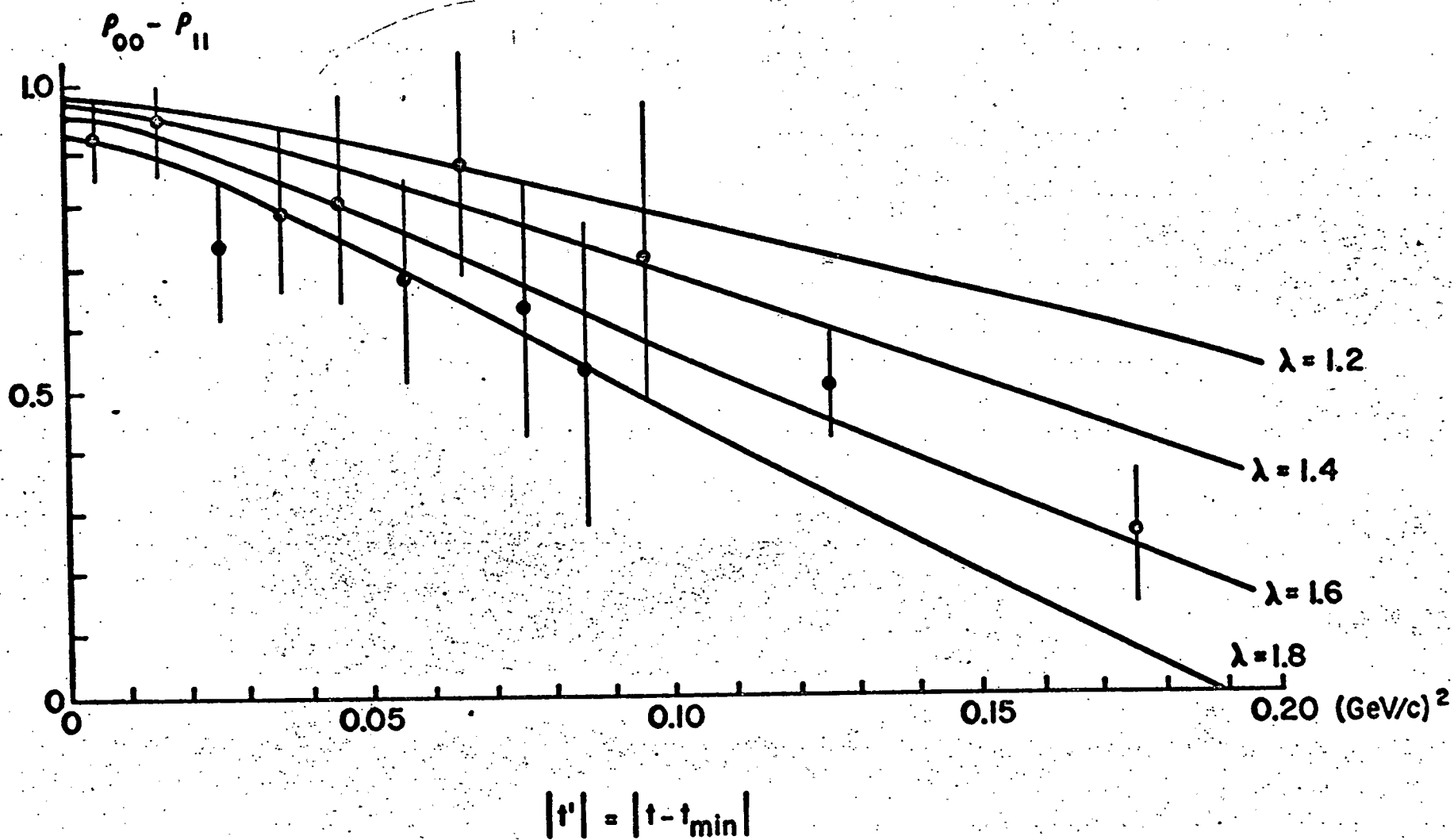
Fig. 5.  $\rho_{00} \frac{d\sigma}{d|t'|}$  for the reaction  $\pi^+ p \rightarrow \rho^0 \Delta^{++}$  at 13.1 GeV/c. The curve is a calculation from the model of Arbab and Brower <sup>(11)</sup> (not normalized to the data).

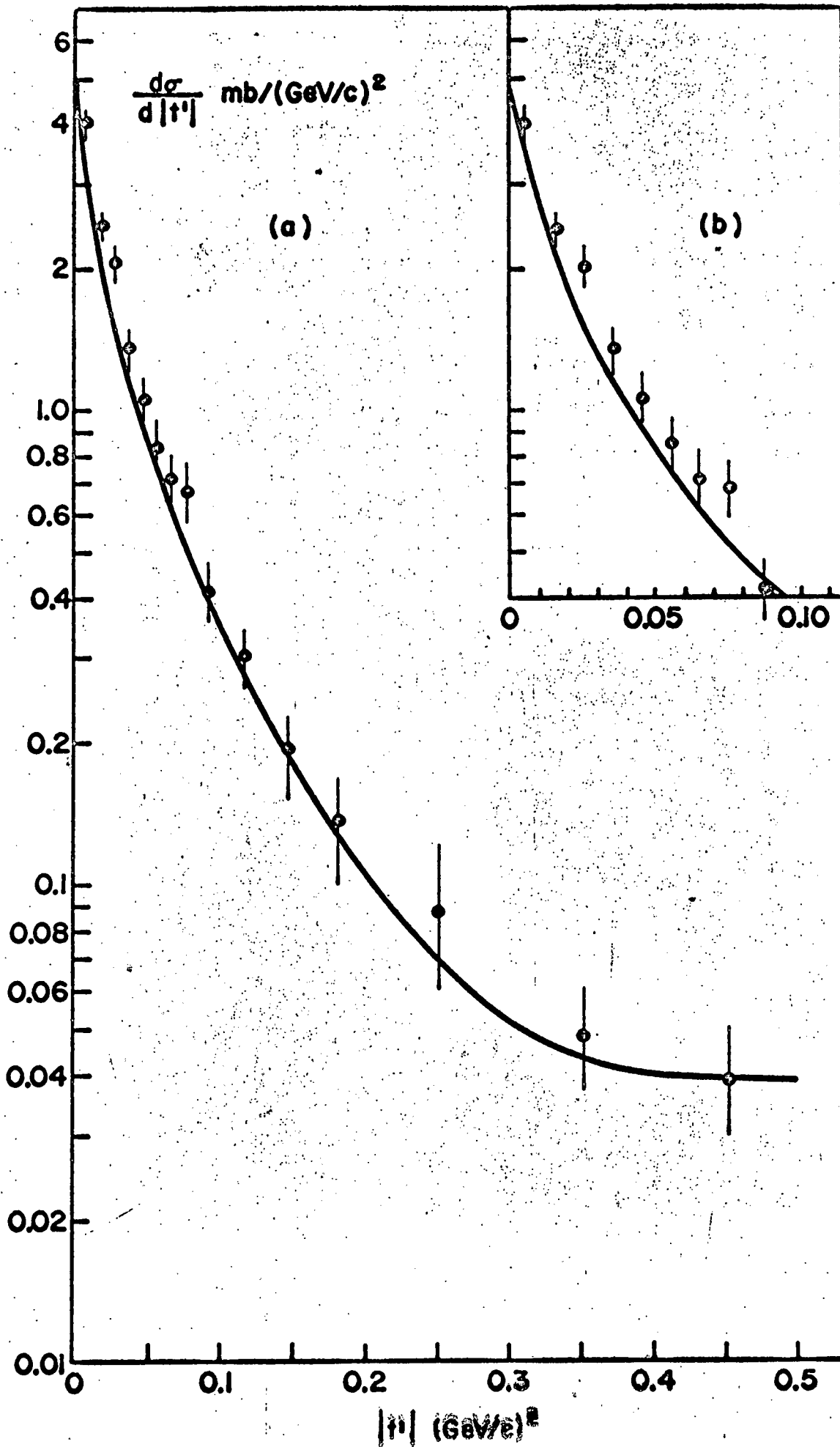
Fig. 6.  $s^2 g_{\rho\gamma}^2 2p_{11} \frac{h}{dt} (\pi^+ p \rightarrow \rho^0 \Delta^{++})$  at 13.1 GeV/c. The smooth curve is discussed in the text.

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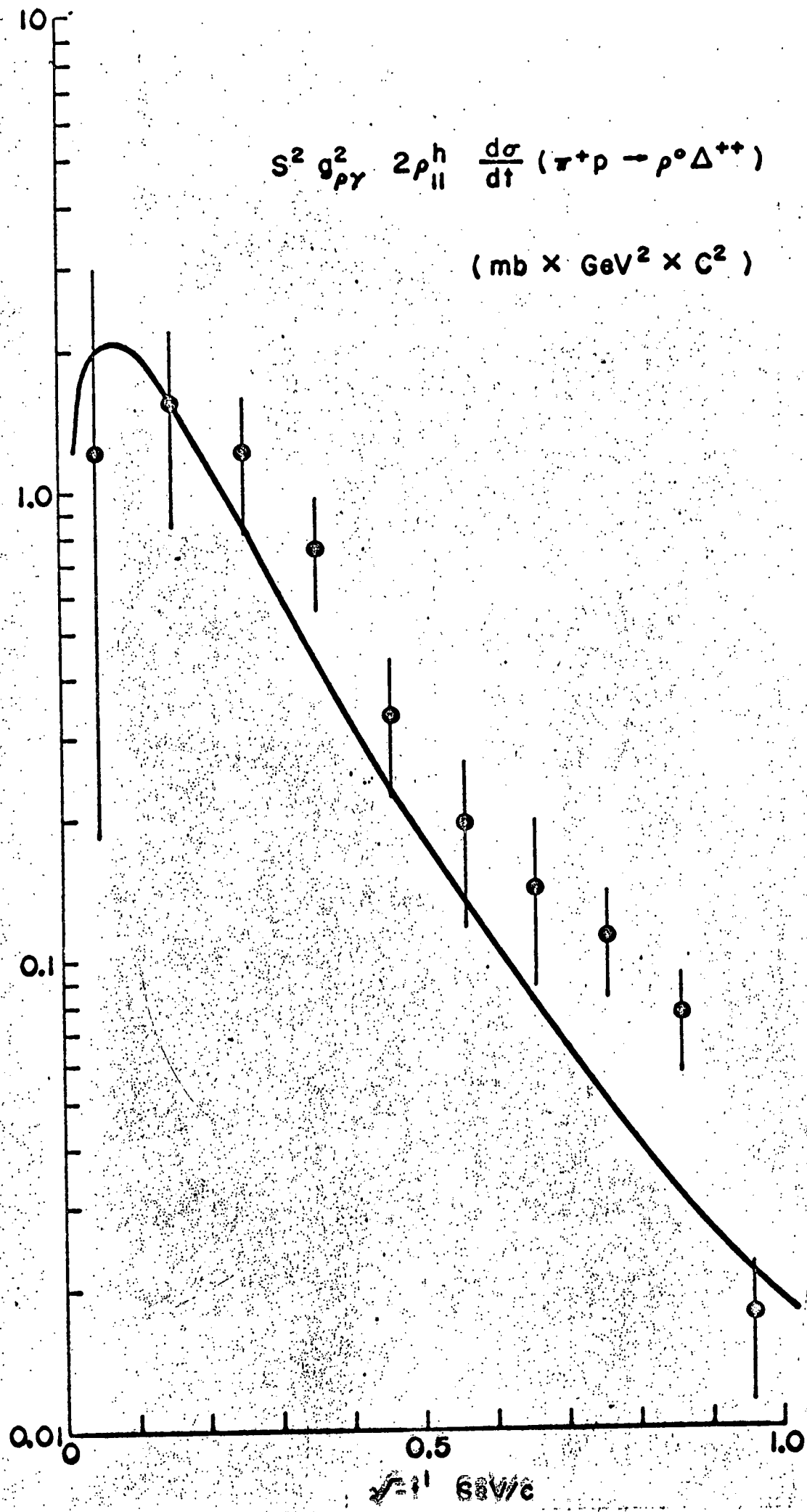


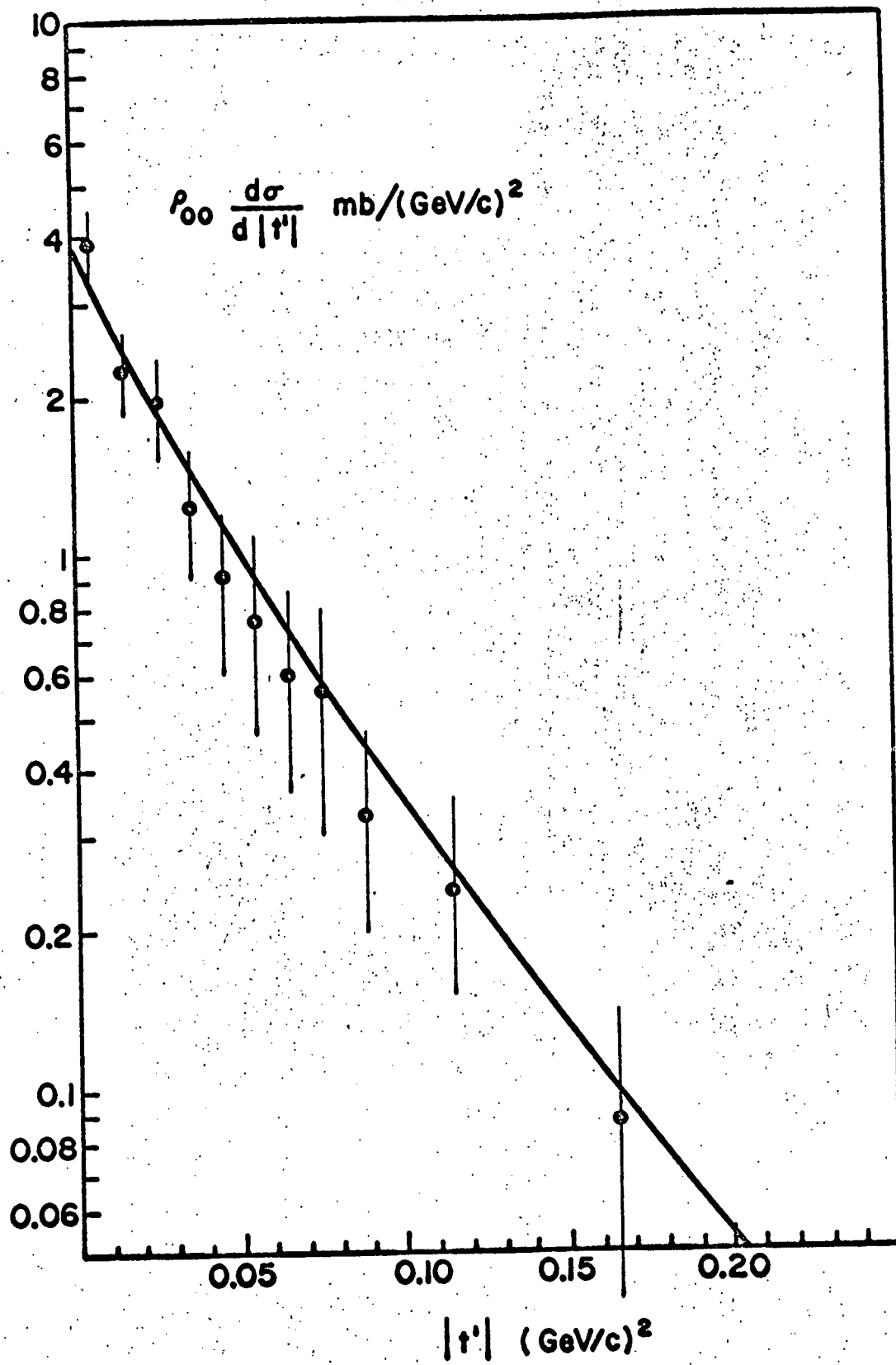
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$$S^2 g_{\rho\gamma}^2 2\rho_{||}^h \frac{d\sigma}{dt} (\pi^+ p \rightarrow \rho^0 \Delta^{++})$$

(mb  $\times$  GeV<sup>2</sup>  $\times$  c<sup>2</sup>)





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