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Particle Physics Using Nuclear Targets*

T. Ferbel

University of Rochester†

We discuss the use of nuclear targets in particle physics and summarize some recent results obtained in studies of hadronic interactions on nuclei. In particular, we present experimental findings on inclusive production and on coherent dissociation of mesons and baryons at high energies.

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Introduction - Why pick on nuclei?

It is, of course, no great secret that nuclei consist of a rather loosely bound conglomerate of neutrons and protons. Most nuclei are not simple spherical objects, far from it, they appear to exhibit high-order moments in their charge and mass distributions. They are generally, in fact, complex multi-particle systems, which some (possibly misguided) scientists consider worth studying for their own sake. Because it can be easily documented that particle physicists view any departure from purity in their research in the dimmest of terms, it has been the custom in recent years to begin a lecture of this kind with a justification for the use of dirty nuclear targets. (In fact, I expect that the true purists will shortly force similar justifications from those researchers in our field who insist on using conglomerates of quarks rather than pristine leptons in examining the properties of elementary particles and their interactions.)

To begin with, nuclear targets are exceedingly cheap and easy to make. Although this may not sound as an important justification for using nuclear targets, it is nevertheless, at least historically, one of the major reasons for their popularity. There are, in addition, many "physics" reasons for using targets other than hydrogen for studying elementary-particle collisions, several of these reasons (especially those pertinent to my interests) are discussed below.

I. Nuclear Coulomb Field

One of the most important reasons for picking on nuclei is that the nuclear coulomb field provides a rich source of photons; in fact, at large distances, we can regard the nucleus as an almost-real photon target that can be used for examining, for example, meson-photon

interactions. The utility of this particular aspect of the nucleus has been recognized now for almost thirty years.[1] A variety of radiative decay widths of unstable elementary particles have been determined from measurements of the coherent production of such particles.[2] The general formalism used for extracting such radiative widths is based on the expected dominance of the one-photon exchange mechanism in inelastic production at smallest momentum transfers (Primakoff Process). The diagram in question is illustrated in Fig. 1a, and the cross section for such electromagnetic production of a particle of mass M* and spin S*, in the field of a target nucleus (A) and charge Z is given by:

$$\frac{d\sigma}{dt} = \frac{2S^* + 1}{2S + 1} 8\pi\alpha Z^2 \left(\frac{M^*}{M^{*2} - M^2}\right)^3 \Gamma_\gamma(M^*) \; |F(t)|^2 \frac{(t-t_{min})}{t^2} \qquad (1)$$

Here t is the square of the four-momentum transfer to the nucleus, F(t) is the nuclear form factor, t_{min} is the kinematic minimum for t, M is the mass and S is the spin of the incident particle, and $\Gamma_\gamma(M^*)$ is the radiative decay width for the process $M^* \to M + \gamma$. (For incident photons the above expression for the cross section must be multiplied by a factor of 2.)

At low energies a competing coherent-production mechanism involves the exchange of mesons (e.g., ω^o); however, above 100 GeV/c in incident momentum, particle-exchange contributions to coherent nuclear processes are expected to be negligible, and consequently the extraction of Γ_γ is expected to be quite reliable. The interference term between the γ-exchange and the ω^o-exchange amplitudes at AGS/PS energies is important and this fact, for example, has been used by sundry prejudiced theorists as an

excuse for not accepting as final the fine measurements of the widths for $\rho^- \to \pi^-\gamma$ and $K^*(890)^o \to K^o\gamma$ decays.[3] At Fermilab energies the γ-ω interference terms should be typically $\lesssim$ 20% for production on a Pb target, and therefore the only questionable matter in extracting Γ_γ might be possible contributions from 2-photon exchanges. These kind of contributions change sign with the charge of the incident particle and they can therefore be checked directly.

Physicists from Fermilab, the Universities of Minnesota and Rochester have just completed an experiment to measure radiative decay widths of a variety of mesons. Preliminary data for the A_1 and ρ are shown in Figs. 2-5. The reactions in question are:

$$\pi^- + A \to \rho^- + A \qquad (2)$$
$$\hookrightarrow \pi^-\pi^o$$

$$\pi^- + A \to A_1^- + A \qquad (3)$$
$$\hookrightarrow \pi^-\pi^+\pi^-$$

The $\pi^-\pi^o$ and $\pi^-\pi^+\pi^-$ mass distributions for data at 150 GeV/c, for production on several nuclear targets, indicate the presence of a clear ρ^- signal and a peak at the A_1, while the steep t-distributions for the ρ^- and A_1^- data, indicate the coherent nature of the process. (The $\pi^-\pi^+\pi^-$ mass spectrum is very similar to that observed at lower energies-in particular the shoulder at $\sim$1250 MeV is akin to that found by the CERN-ETH group.[4]) Cross sections for coherent ρ^- production scale essentially as Z^2, while the A_1 signal has a far weaker A-dependence. Although the experiment ended only a month ago, we have a preliminary value for the radiative width of the ρ^-. We obtain $\Gamma(\rho^- \to \pi^-\gamma) = 50 \pm 10$ KeV, a value essentially consistent with the previous measurement of Gobbi et al.[3] I do not have sufficient time to discuss the many internal checks on the reliability of this measurement, but a brief description of the experiment will be published in the proceedings of this meeting.[5] In any event, it appears that the ρ^- radiative width

is well below the expected $\sim$ 100 KeV, and it remains to be understood why this is the case.

In addition to providing a means for extracting radiative widths of elementary particles, production in the nuclear coulomb field can be used, for example, to obtain non-resonant K-π and π-π scattering phase shifts in an unambiguous manner.[6] Also, phases of the hadronic amplitudes, particularly those produced diffractively - can be ascertained by studying their interference with the electromagnetic process.

Our preliminary data on A_1^- production still suffer from use of first-order reconstruction programs. Once these are more fully developed and our resolution maximized we expect to observe at smallest t-values contributions from the direct coulomb production of the A_1 (as displayed in Fig. 1a) as well as from non-resonant electromagnetic production (see, for example, graph in Fig. 1b). Note that contributions akin to Fig. 1b should not be present in the case of ρ^- production, while for the A_1 peak these must be present and, besides interfering with the diffractive production amplitude, they <u>must</u> interfere with the resonant term of Fig. 1a (if that is indeed present!). Regarding Fig. 1b, I might add that the inverted diagram (ρ^o-exchange) clearly cannot contribute because of C-invariance.[7] The preliminary results on A_1^- production indicate that its radiative width is well below the expected 1000 KeV value.[8] (For comparison see Fig. 6, where a clear coulomb peak is observed in neutron-dissociation for a radiative width of about 500 KeV.) In fact, our upper limit for $\Gamma(A_2^- \rightarrow \pi^-\gamma) \lesssim 60$ KeV is also well below the expected value of $\sim$500 KeV.[8] Consequently, it appears that the most straightforward predictions for the radiative widths of mesons refuse to be supported by stubborn nature!

II. Nuclear Targets for Studying Diffractive Excitation

Hadronic reactions of the type in which nuclei remain intact (particularly in their ground states) serve as selective filters for producing certain specific kinds of particle states.[9] Ignoring helicity-flip contributions (which are in fact non-negligible - except at zero degrees) only mesons with spin parity $J^P = \ell^{\ell+1}$ can be formed via Pomeranchukon ($\mathbb{P}$) exchange. (Here ℓ is the orbital wave in the excitation of the incident meson to a meson of spin $J = \ell$.) Although the A_2^- cross section on hydrogen in Reaction (3), for example, has a very weak energy dependence, and the A_2 has been observed in coherent production off nuclei at lower energies,[10] it is still an open question whether spin-flip can occur in diffractive production. Our preliminary cross sections for A_2^- production (in the $\pi^-\eta^o$ decay mode) off nuclei are very small; in fact, on a Pb target the ratio of A_2/A_1 production appears to be at most one half of that observed at lower energies, suggesting that the energy dependence of the helicity-flip contribution to coherent production is too severe to be due mainly to $\mathbb{P}$-exchange. If this result holds up with improvement in our analysis it will lend strong support to the validity of the Morrison rule in diffractive production.[11]

In addition to serving as a selective filter, the nuclear target is also highly sensitive to the nature of the mechanism responsible for diffractive production.

A year ago we presented some unusual results from the Rochester-Northwestern-Fermilab-SLAC collaboration on coherent neutron dissociation.[12] Several features of those data are repeated in Figs. 7 and 8. In Fig. 7 I display the decay angular distributions of $(p\pi^-)$ systems produced in the reaction:

$$n + A \rightarrow (p\pi^-) + A \qquad (4)$$

The angle θ_{GJ} is the polar angle of the proton in the Gottfried-Jackson rest frame of the $(p\pi^-)$ system. (The z-axis of quantization is the neutron beam direction in the $(p\pi^-)$ rest frame.) The data are for Cu and C targets and different regions of $(p\pi^-)$ mass (M). We have used a simple production model, based on the Deck mechanism, to see if the data follow the predicted behavior. The same model[13] was used with surprising success in our investigation of Reaction (4) on hydrogen.[14] The general features of the hydrogen data (except for a factor of two in normalization) were described adequately by adding the amplitudes for the graphs given in Fig. 9. In Fig. 10 I show the kind of fits we obtained for Reaction (4) on hydrogen. At smallest masses all the terms in Fig. 9 are large, and, in fact, their interference terms are also important. As the masses increase the contribution from the direct term becomes small and the π-exchange and p-exchange terms separate in phase space and the interference terms become unimportant. The model applied to the nuclear data, again appears to provide a good framework for understanding the source of asymmetries and anisotropies in θ_{GJ} at all M. The model also predicts, albeit roughly, the t-dependence of the data. (Again, the overall predicted normalizations are too high - possibly due to neglect of absorption - and I have displayed the calculations reduced by a factor of 4 for Cu and a factor of 3 for C.) Consequently, it seems that the Deck-like model provides an excellent first-order description of the diffractive dissociation phenomenon at high energies, and that the properties observed, in hydrogen as well as in the nuclear data, clearly indicate the need for all the terms shown in Fig. 9. In fact, from the viewpoint of model-building, the nuclear data are probably more interesting than hydrogen because the less understood baryonic-exchange

contributions are more important at smallest momentum transfers. From these comparisons I conclude that at small M the contributions from both π-exchange and p-exchange do not drop rapidly enough in θ_{GJ}; which suggests that both propagators must have more drastic form factors than present phenomenology affords. (At larger masses, resonance contributions could be called into the picture to provide greater flexibility in the model.)

III. Examining Hadronic Processes In Their Nascency

Nuclear targets have been used in the past to obtain cross sections for the interaction of unstable-particles with nucleons.[15] The idea is based simply on the fact that, once produced, the unstable particle is attenuated on its way out of the nucleus. Consequently, the larger is its absorption cross section, the less chance is there for the unstable particle to leave the nucleus without interacting. In principle, therefore, the A-dependence of the coherent production of some specific object should contain folded into it the cross section for the interaction of that object with nucleons within that nucleus. The extraction of this cross section is, not surprisingly, model dependent. The historically favored optical model has been that of Margolis.[16] (Experimenters like it because its predictions are relatively easy to calculate.)

Several groups have obtained total cross sections for the interactions of unstable multi-particle systems with nucleons. The results can be summarized as follows: 1) The cross sections appear to depend on the spin of the system;[17] 2) The cross sections depend on the mass of the system;[18] and, 3) Typically, the cross sections extracted for the scattering of multiparticle systems are smaller than for the scattering of elementary particles.[18,19] The last result has been attributed

to the neglect of helicity-flip contributions in the Kölbig-Margolis formulation.[20] Figure 11 displays the mass-dependence of the total cross section for multiparticle systems. (Data are from references 18, 19 and 21.) In any case, it appears from these studies that nuclear matter is far more transparent to multiparticle systems than initially envisioned. More theoretical work is required to gain a better understanding of this effect and for obtaining a less model dependent way to extract cross sections for scattering of these coherently-produced unstable objects.

Finally, I will speak on inclusive particle production using nuclear targets. There has been a great regeneration of interest in this field and excellent reviews of the experimental work are available in the literature.[22] One of the crucial issues in this area of research pertains to the space-time development of hadronic processes, particularly as reflected in produced-particle multiplicities. If, for example, elementary hadronic interaction times were short (i.e., if the asymptotic states we measure experimentally evolved on time scales of the order of nuclear traversal times, namely, $\tau \sim 10^{-23}$ sec) then produced-particle multiplicities in nuclei would be expected to be far greater than on hydrogen; this because of the increase in the multiplicity resulting from secondary interactions of particles produced within the nucleus (cascading). Such cascading might not be expected to be important at low incident energies, but should certainly become apparent (if $\tau \sim 10^{-23}$ sec) for momenta greater than $\sim$100 GeV/c. Figure 12 presents the differential multiplicity as a function of laboratory rapidity for negative (a) and for positive (b) particles produced in $\sim$300 GeV/c neutron-nuclear collisions. The data are for Be, Al, Cu, Sn and Pb targets, displayed in increasing order in A (top to bottom); for clarity, each data set is displaced relative to the

one for the previous target by one decade in multiplicity. The multiplicity on hydrogen was not measured in this experiment,[23] but it is expected to be ~ 1 both for positive and for negative particles near a rapidity $y \sim 3$. (The neutron beam is a broad band beam with an average momentum of ~ 300 GeV/c, consequently, a value of $y \simeq 3$ corresponds to production at 90° in the center of mass.) The kind of data displayed in Fig. 12 clearly exclude models which allow any substantial amount of cascading in the nucleus.

It is common to parameterize the A-dependence for inclusive data in terms of a parameter α, with the cross sections fitted to the form A^{α}. The value of α as a function of y for the data in Fig. 12 is given in Fig. 13. For both positively and negatively charged particles, α appears to be ~ 0.85 near $y_{CM} \sim 0$ and falls monotomically to ~ 0.55 for largest rapidities. When α is examined as a function of the angular variable (pseudo rapidity) $\eta = -\ln \tan\theta/2$, in Fig. 14, the dependence appears to be somewhat different. For $\eta \simeq 3$ the value of α is still about 0.85, but α does not fall below $\alpha = 0.7$ at large η. In fact, α appears to increase dramatically for $\eta \gtrsim 7$.[24] Although it is tempting to attribute this kind of effect to electromagnetic processes (recall that Reaction (4), for example, has large contributions from coulomb production of low-mass ($p\pi^-$) systems, the decays of which appear at very small laboratory angles), the fact that both positive and negative particles exhibit similar behavior speaks against this interpretation. In addition, examining positive particles with momenta in excess of 80 GeV/c (mainly protons) suggests, because here α is ~ 0.6, that coulomb production may not be the answer to the rise of α at large η (see part (d) of Fig. 14). The rise does not appear to be restricted to any particular range of momenta. It is interesting that our observed dependence of $\alpha(y)$ can be accommodated using a variety of models.[25] The predictions of CTM[26] are sketched in Figs. 13 and 14.

As mentioned previously in this paper, the slow growth of multiplicity with increasing A-values has established that elementary hadronic interaction times are long compared to 10^{-23} sec. In addition, other general features of inclusive data on nuclei have been of value in gaining an insight into hadron-hadron scattering. For example, the fact that α falls below a value of ~ 0.7 can be interpreted as meaning that cut contributions, in addition to single Regge-pole exchanges, must occur in inclusive production. (For a value of $\alpha = 0.7$ in nucleon-A collisions there is no dependence of multiplicity on A.) The fact that α always increases with increasing p_T (and even exceeds $\alpha=1$ at very large p_T) has been attributed with considerable success to parton-parton hard scattering.[27] (A similar rise of α with p_T is found for dihadron production.[28])

Another general feature of the data, one that is not as yet easily interpretable, is a rise in α at smallest p_T.[29] This effect is displayed for the neutron data[23] in Fig. 15. Both positive particles (a), negative particles (b), positive particles with momenta below 80 GeV/c - mainly π^+ - (c) and positive particles with momenta in excess of 80 GeV/c - mainly protons - (d) appear to show a rise in α at small p_T^2. (The data are for $y_{LAB} > 4$.)

A Michigan, Rutgers-Wisconsin Collaboration has studied the production of K_S^o, Λ and $\bar{\Lambda}^o$ in p A collisions.[30] Their data display many of the features observed in the production of majority particles. Figure 16 shows their differential multiplicity spectra for K_S^o and Λ^o production on Be, Cu and Pb nuclei. There is clear evidence for strong attenuation of strange particles with increasing A, not dissimilar to the kind of effects observed for pions. The values of α are more akin to those found for protons than for pions (see Fig. 13 d). The experiment also finds an increase of α with increasing p_T.[30]

The dependence of multiplicity on the quantum numbers of the projectile has been examined by the MIT-Fermilab group.[31] They find that the differential multiplicity does not depend on the incident particle when the nuclear thickness of the target material is expressed in terms of the parameter $\bar{\nu} = A\,\sigma_{hp}/\sigma_{hA}$, where σ_{hp} and σ_{hA} are the inelastic hadron-proton and hadron-nucleus total cross sections. (The parameter $\bar{\nu}$ reflects the average number of inelastic collisions a projectile (h) would undergo in traversing a nucleus of atomic number A.) This group's most recent 100 GeV/c data pertaining to this question are given in Fig. 17. (The ordinate $r(\eta)$ is the differential multiplicity divided by that on hydrogen.) The result is quite interesting; it implies that, subsequent to the initial collision, produced particles tend to behave as if they were identical to the incident hadron!

The above results, taken together with the known increase in pion multiplicity with increasing number of observed protons,[32] brings to mind the following picture of hadron-nucleus collisions: the process involves multiple exchanges between several nucleons and the incident object, or its continuation in the form of a primary core, having the quantum numbers of the projectile. As usual, multiplication only occurs in the region of small rapidity, where rescattering contributes; at large rapidities there is little multiplication because the energetic primary cluster of particles (or leading energy flux) behaves as one object as it traverses the nucleus (some attenuation can take place at largest rapidities - if for no other reason than from momentum conservation). This kind of picture is qualitatively consistent with most current models of production in nuclei.

As an afterthought to this section I want to mention a very nice result from the Michigan-Rutgers-Wisconsin Collaboration.[30] The group extrapolated their inclusive Λ^o production measurements from nuclear targets to hydrogen, and fitted their extrapolated production spectra to a triple-Regge expression. Their extracted value of the effective Regge trajectory, as a function of t (proton to Λ^o) is shown in Fig. 18; the reaction appears to be dominated by the K* trajectory. These nice results speak for themselves and clearly point to another of the many utilities of cheap nuclear targets.

I thank Dr. K. K. Phua for inviting me to speak at the Singapore Meeting. I also wish to express my gratitude to my collaborators for their help in obtaining and in analyzing the data presented here. In particular, for the inclusive data I thank D. Chaney and the members of the Rochester-Northwestern-Fermilab Collaboration: P. Slattery, D. Underwood, University of Rochester; B. Gobbi, R. Lipton, J. Rosen, R. Ruchti and D. Spelbring, Northwestern University; E. Bleser and D. Johnson, Fermilab. For the coherent neutron dissociation data I wish to single out the recent contributions of L. Golding, W. Ford and W. Mollet, in addition to those collaborators listed above. Finally, I acknowledge the excellent cooperation of the members of our recently completed Fermilab experiment E272: D. Berg, C. Chandlee, S. Cihangir, Y. Fukushima, T. Jensen, F. Lobkowicz, C. N. Nelson, Jr., T. Ohshima, P. Slattery, and P. Thompson, University of Rochester; K. Einsweiler, T. Joyce, Y. Makdisi, M. Marshak, E. Petersen, K. Ruddick and T. Walsh, University of Minnesota and J. Biel, T. Droege, P. F. Koehler and A. Jonckheere, Fermilab.

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Figure Captions

1. Diagrams relevant to particle production in the nuclear coulomb field: (a) Primakoff production of a resonance M*, (b) non-resonant graph contributing to the electromagnetic production of the A_1.
2. Cross sections for the coherent production of $\pi^-\pi^0$ pairs off several nuclei at 150 GeV/c.
3. Mass distributions for the coherent production of $\pi^-\pi^+\pi^-$ systems off several nuclei. Although the overall normalization is arbitrary, relative normalizations among the nuclear targets are good to $\sim$10% accuracy. (The mass distribution summed for all nuclei is also shown in Fig. 3'.)
4. Distributions in the square of the momentum transfer for coherent production of $\pi^-\pi^0$ masses in the ρ^- region. (Relative normalization among nuclei is reliable to $\sim$10% accuracy.)
5. Distributions in the square of the momentum transfer for coherent production of $\pi^-\pi^+\pi^-$ masses in the A_1 region. (Relative normalizations reliable to $\sim$10% accuracy.)
6. Neutron dissociation from a carbon target at 200 GeV/c. The steep rise in the cross section at $t \lesssim 0.002$ GeV^2 is due to the coulomb production of $\Delta^0(1236)$.
7. Gottfried-Jackson polar-angle distributions for the proton in the decay of $(p\pi^-)$ systems produced coherently off Cu and C targets. The predictions of a Deck-like model (Fig. 9) are shown renormalized to the data at small masses. Magnitudes of the contributions from the three (interfering) terms in Fig. 9 are shown on the Cu results for $1.3 < M < 1.4$ GeV.
8. Comparison of t-distributions for the Cu data of Fig. 7 with the model of Fig. 9. (The theoretical predictions have been reduced by an arbitrary factor of 4.)

9. Diagrams contributing to neutron dissociation into ($p\pi^-$) systems.

10. Comparison of predictions of the production model (reduced by a factor of 2) with data off a hydrogen target at small values of t. (Comparison of predictions as a function of t are displayed in Fig. 10' taken from Ref. 14.)

11. Total cross sections for interactions of unstable-particle systems with nucleons.

12. Differential multiplicity as a function of laboratory rapidity, integrated over p_T, for neutron-nucleus collisions at ∿300 GeV/c. The nuclei are Be, Al, Cu, Sn and Pb from top to bottom. Data for negative particles are given in (a), positive particles in (b). (y has been calculated assuming a pion mass.) The total inelastic cross section was taken to be 46 $A^{0.69}$ mb.

13. The nuclear dependence of the inclusive cross section for (a) all negative particles (mainly pions), (b) all positive particles, (c) positive particles having laboratory momenta below 80 GeV/c (mainly pions) and (d) positive particles having laboratory momenta in excess of 80 GeV/c (mainly protons). A constant value of $\alpha = 0.69$ would correspond to an A-independent multiplicity.

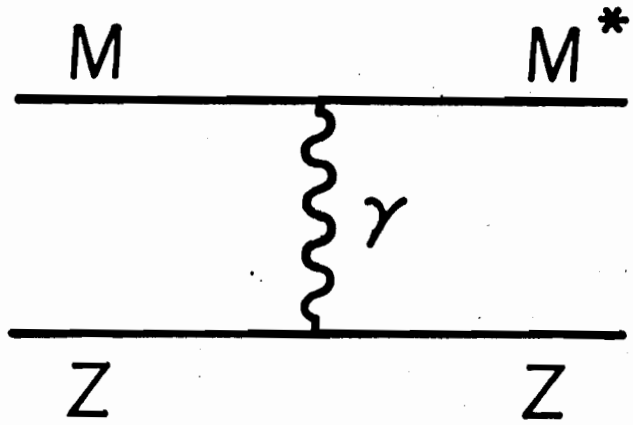
14. The α parameter as a function of η for the same data as given in Fig. 13. (Also in Fig. 14' are the results of Ref. 24. The parameter $\alpha' = \alpha - 0.69$.)

15. The variation of α with p_T^2 for the three categories of data described in Fig. 13 for $y > 4$. (The dependence on longitudinal momentum is provided in Fig. 15'.)

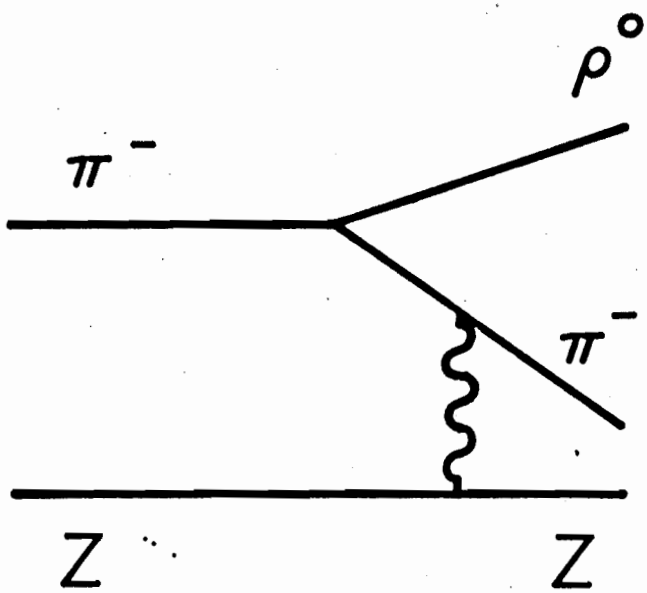
16. Differential multiplicity for Λ^o and K_s^o production off nuclei at 300 GeV/c ($p_T = 0$).

17. Dependence of the differential multiplicity, relative to hydrogen, for different projectiles at 100 GeV/c.

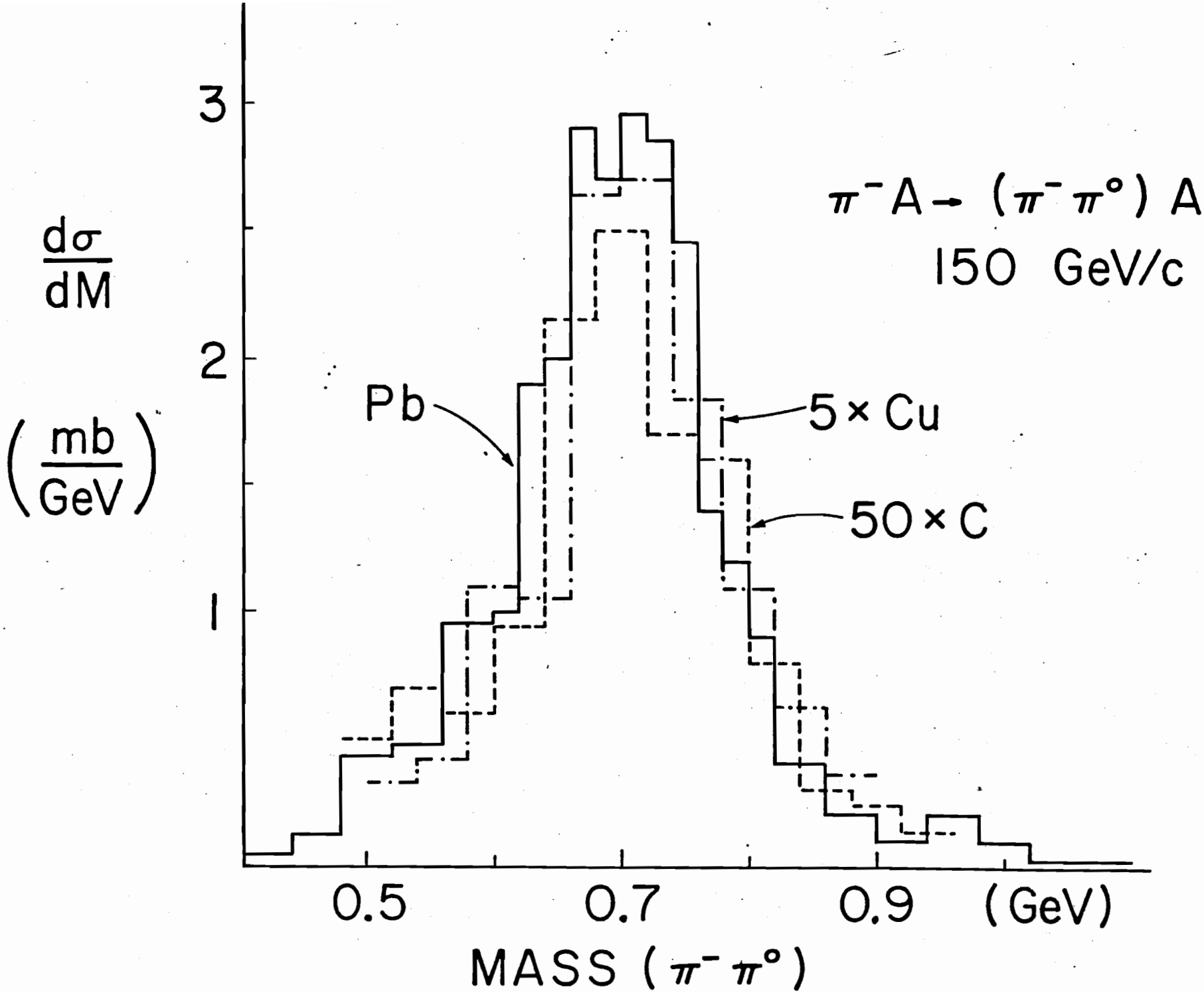
18. Extraction of the effective Regge trajectory contributing to inclusive Λ^{o} production at large rapidities.

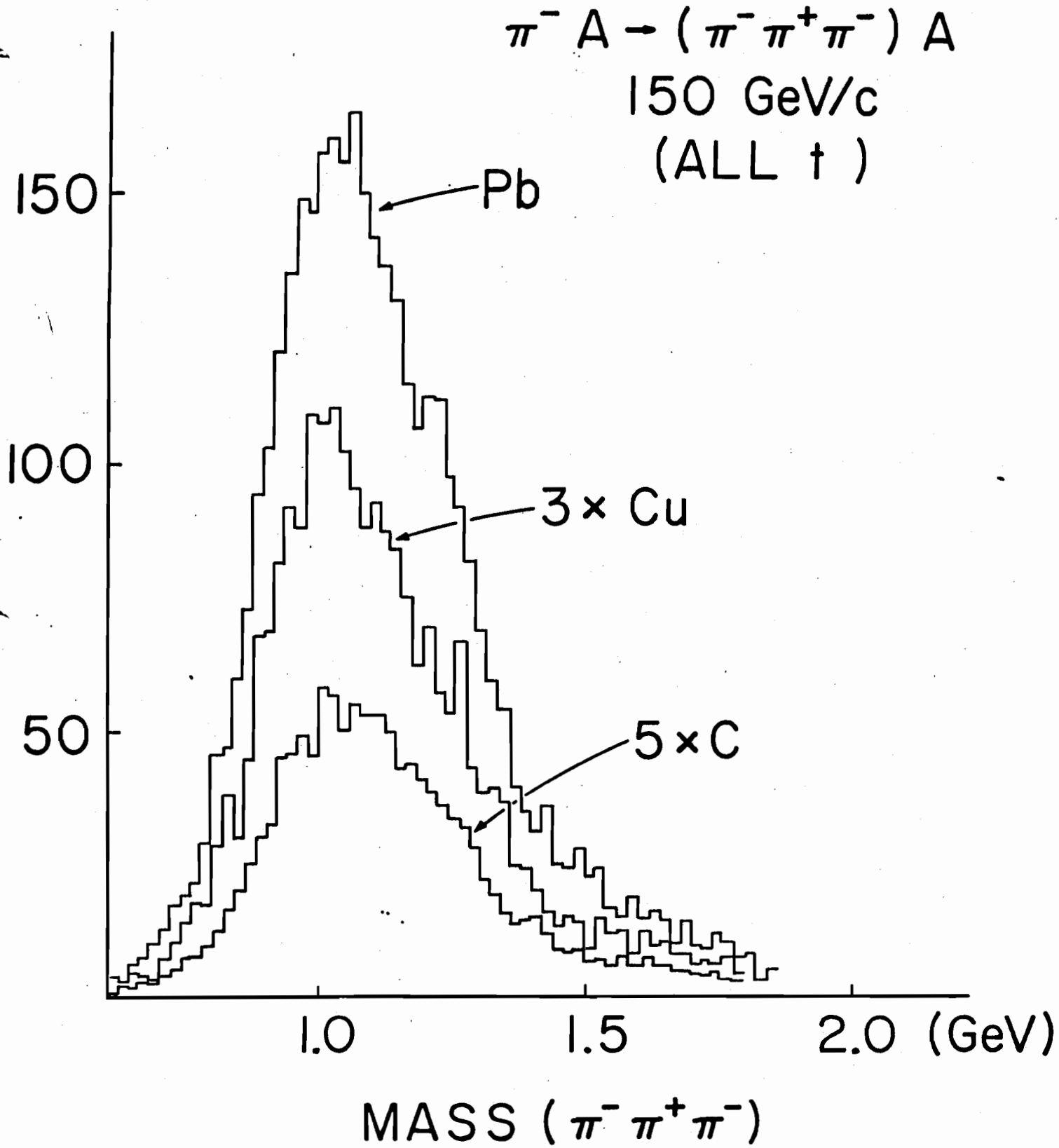


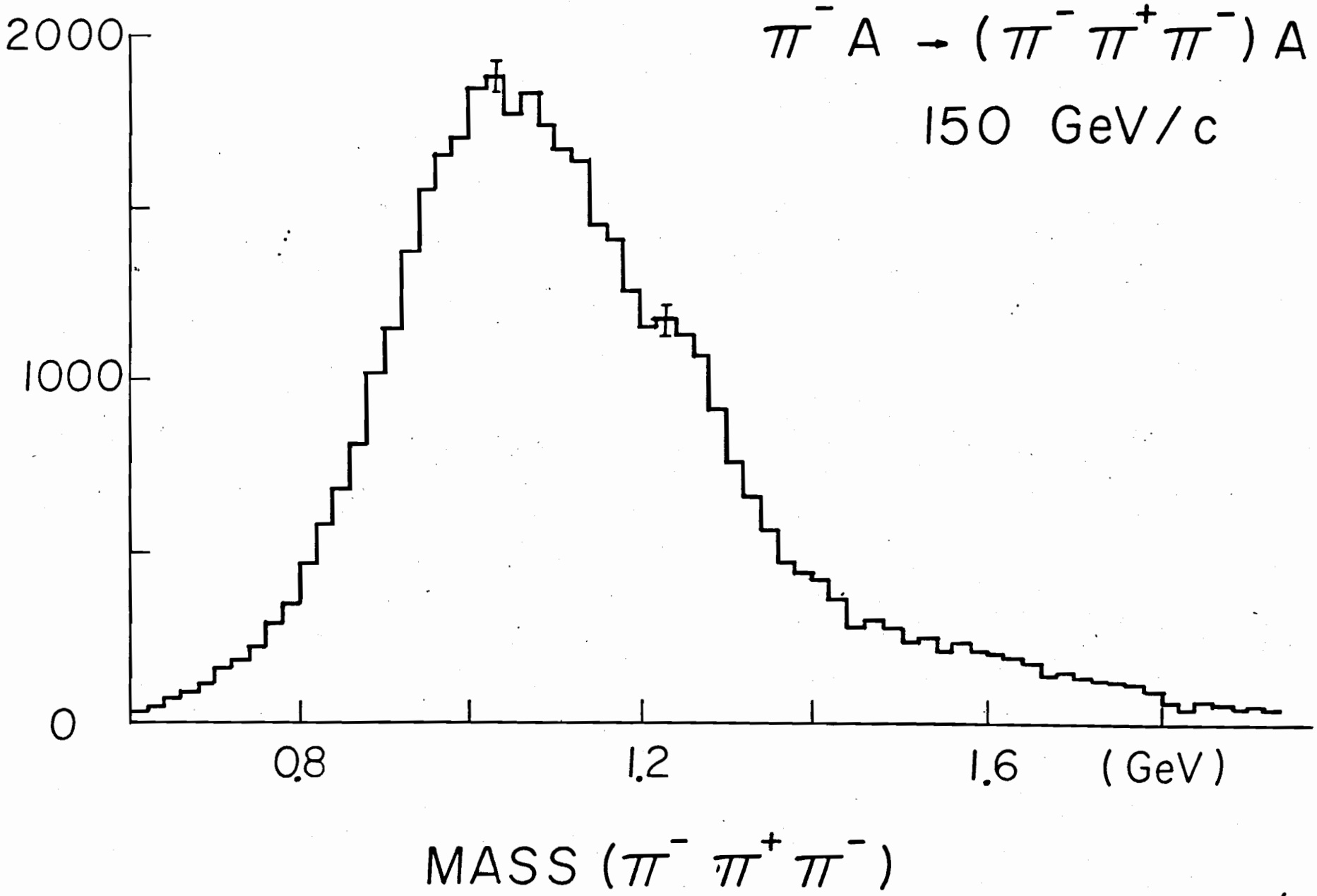
(a)



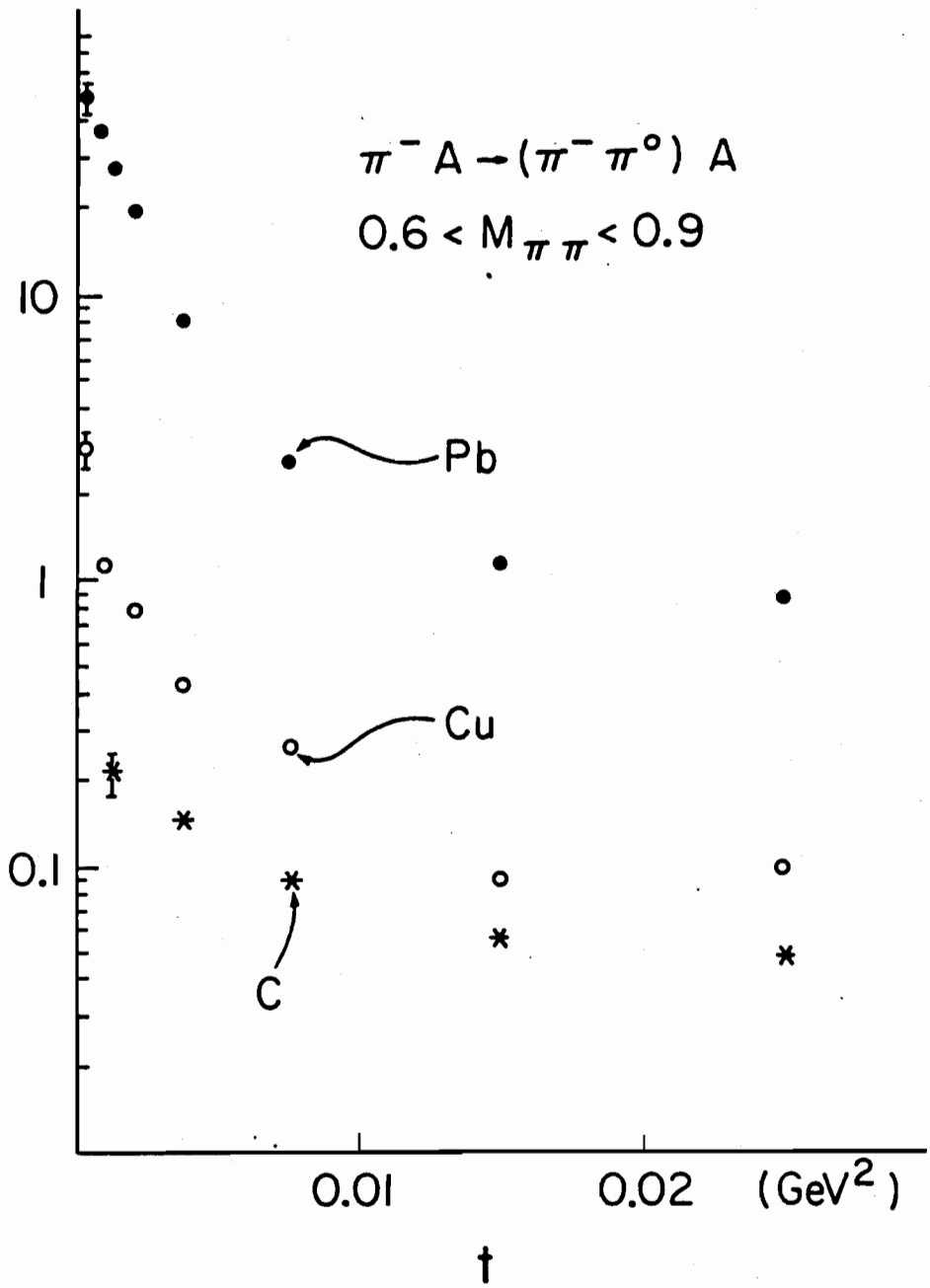
(b)

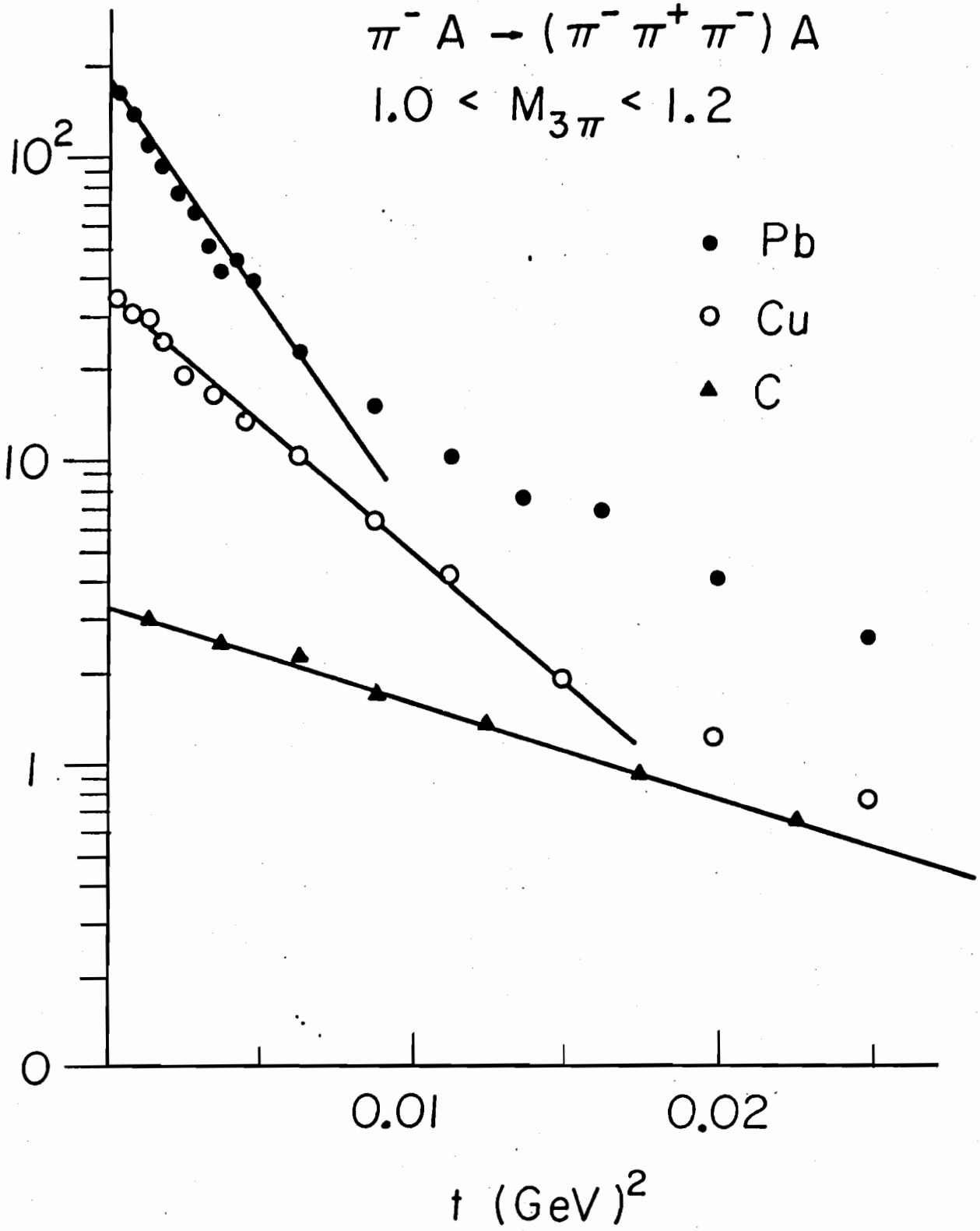

$\pi^- A \to (\pi^- \pi^0) A$
150 GeV/c
$\frac{d\sigma}{dM}$
$\left(\frac{mb}{GeV}\right)$
3
2
1
Pb
5 × Cu
50 × C
0.5
0.7
0.9
(GeV)
MASS ($\pi^- \pi^0$)

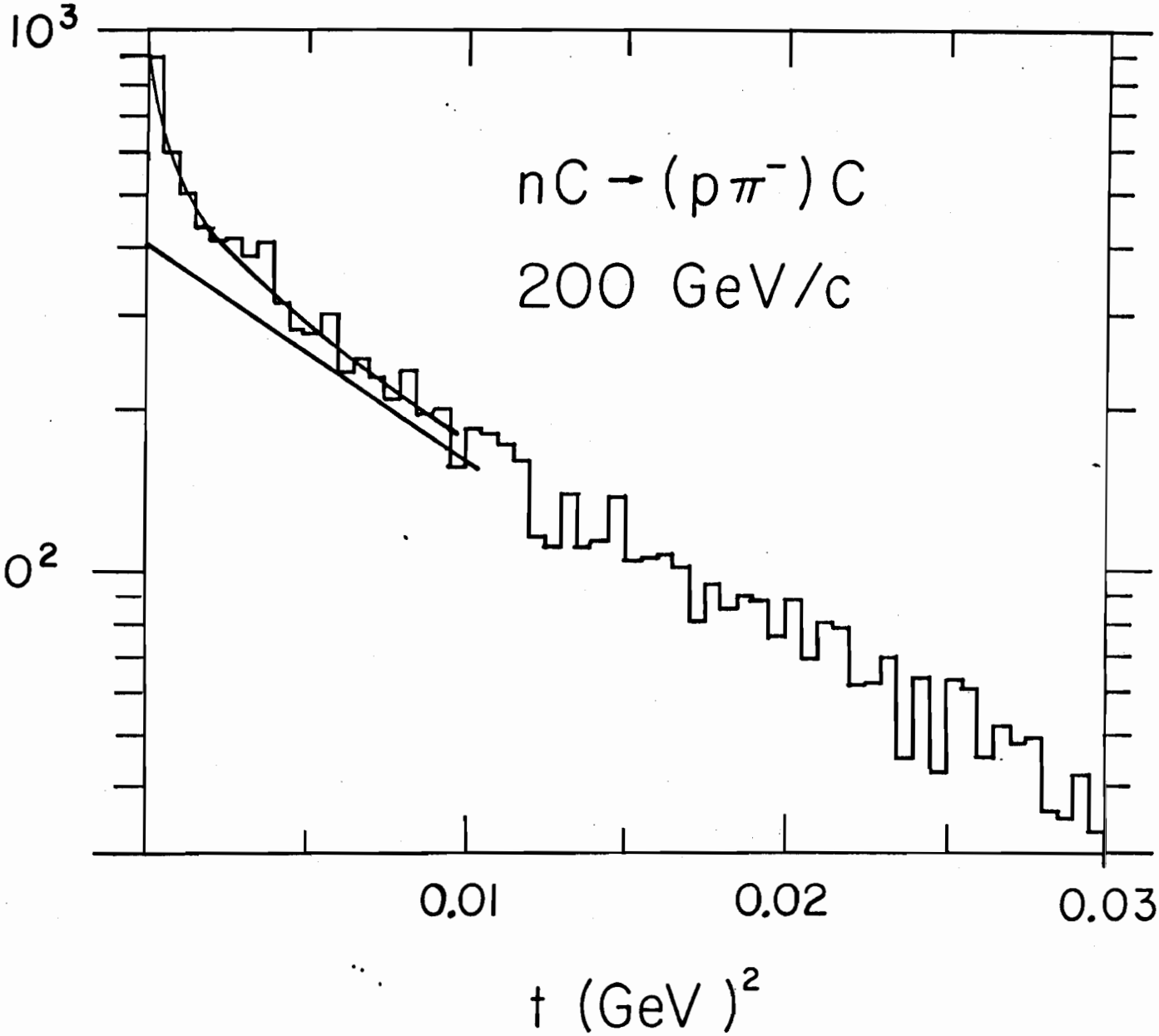

$\pi^- A \rightarrow (\pi^- \pi^+ \pi^-) A$
150 GeV/c
(ALL t)
150
100
50
Pb
3 × Cu
5 × C
1.0
1.5
2.0 (GeV)
MASS ($\pi^- \pi^+ \pi^-$)

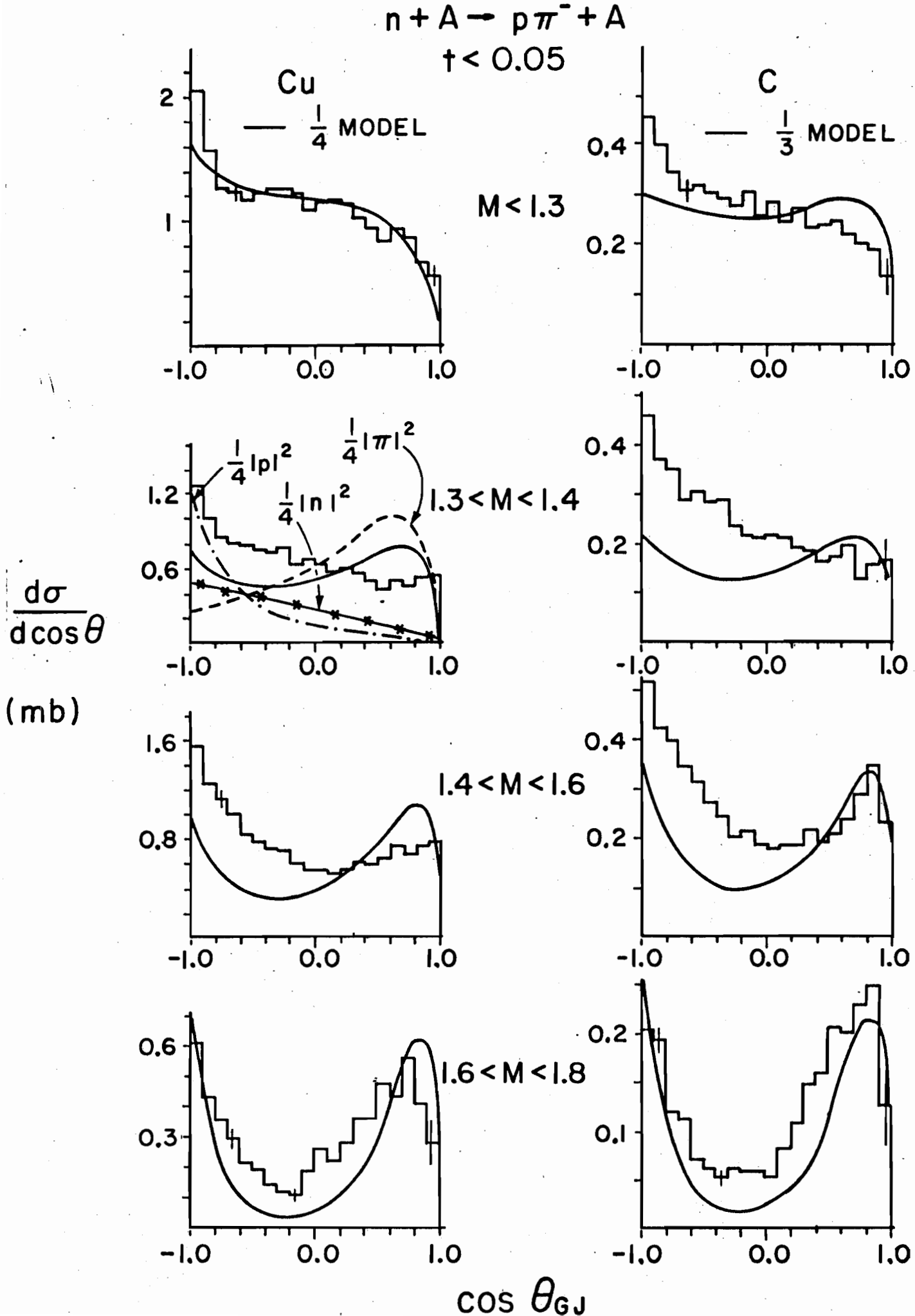

$\pi^- A \rightarrow (\pi^- \pi^+ \pi^-) A$
150 GeV/c
2000
1000
0
0.8
1.2
1.6
(GeV)
MASS $(\pi^- \pi^+ \pi^-)$

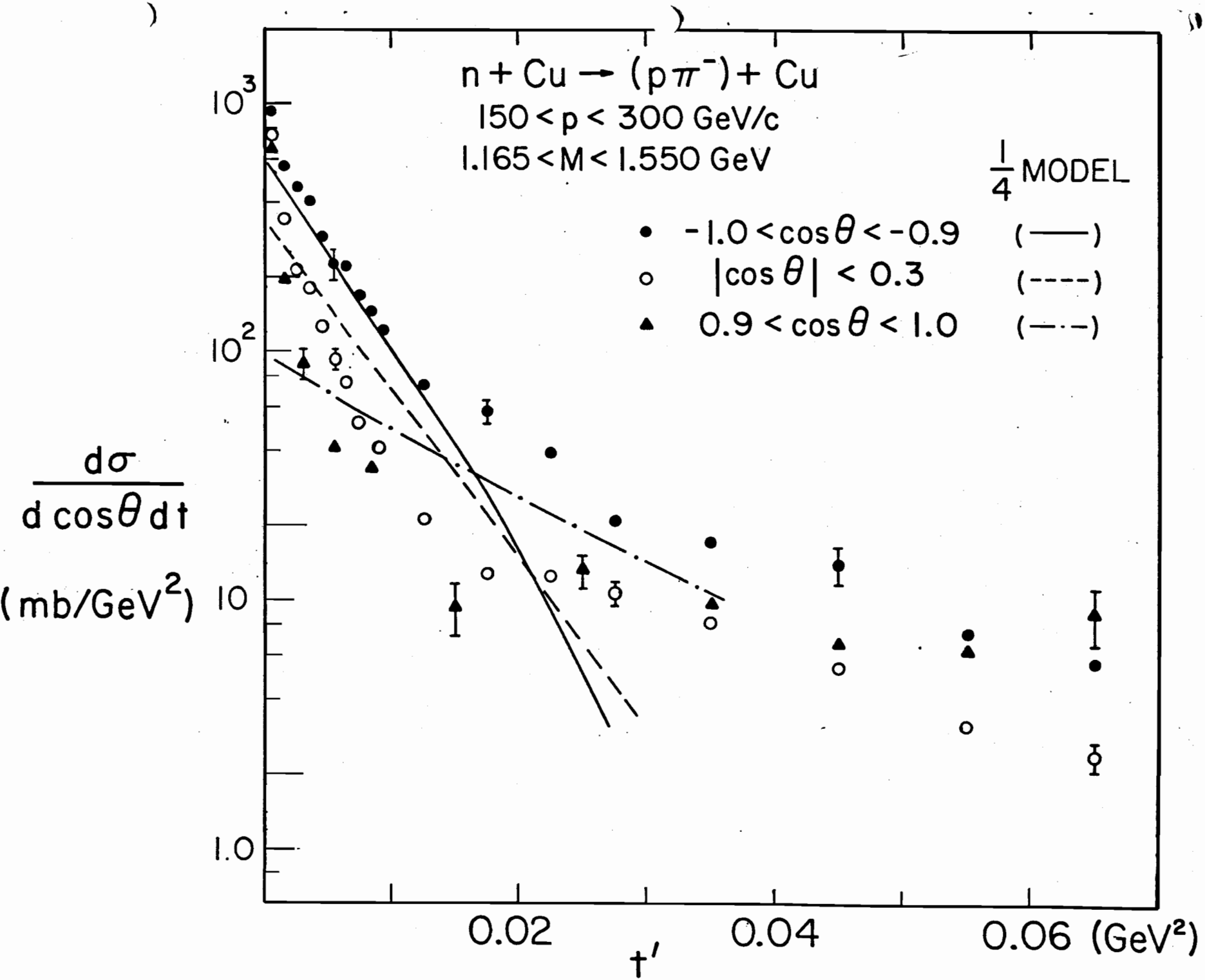
3'


$\pi^- A \to (\pi^- \pi^0) A$
$0.6 < M_{\pi\pi} < 0.9$
10
1
0.1
Pb
Cu
C
0.01
0.02
(GeV^2)
t

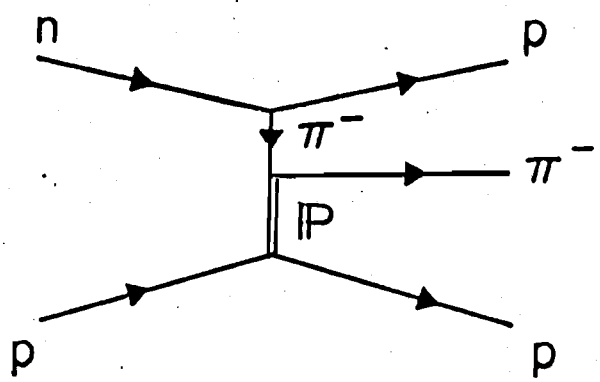

$\pi^- A \rightarrow (\pi^- \pi^+ \pi^-) A$
$1.0 < M_{3\pi} < 1.2$
Pb
Cu
C
10^2
10
1
0
0.01
0.02
$t\ (\mathrm{GeV})^2$


10^3
10^2
$nC \rightarrow (p\pi^-)C$
200 GeV/c
0.01
0.02
0.03
t (GeV)^2

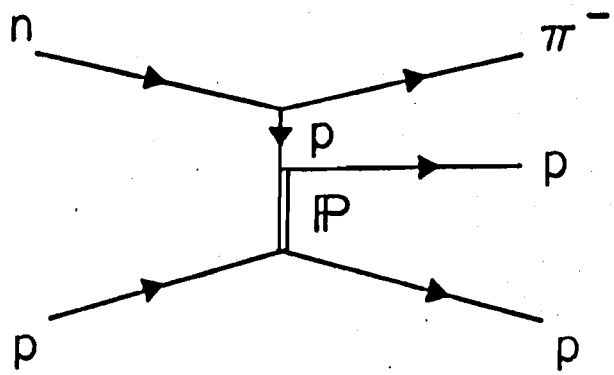

n + A → pπ⁻ + A
t < 0.05
Cu
C
1/4 MODEL
1/3 MODEL
M < 1.3
1.3 < M < 1.4
1.4 < M < 1.6
1.6 < M < 1.8
1/4 |p|²
1/4 |π|²
1/4 |n|²
dσ/dcosθ
(mb)
cos θGJ
-1.0
0.0
1.0


n + Cu → (pπ⁻) + Cu
150 < p < 300 GeV/c
1.165 < M < 1.550 GeV
1/4 MODEL
-1.0 < cos θ < -0.9 (——)
|cos θ| < 0.3 (----)
0.9 < cos θ < 1.0 (—·—)
dσ / d cos θ dt
(mb/GeV²)
10³
10²
10
1.0
0.02
0.04
0.06 (GeV²)
t′

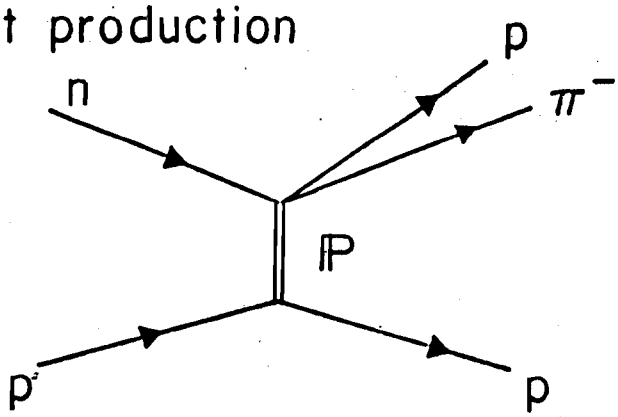
(a) pion exchange Deck

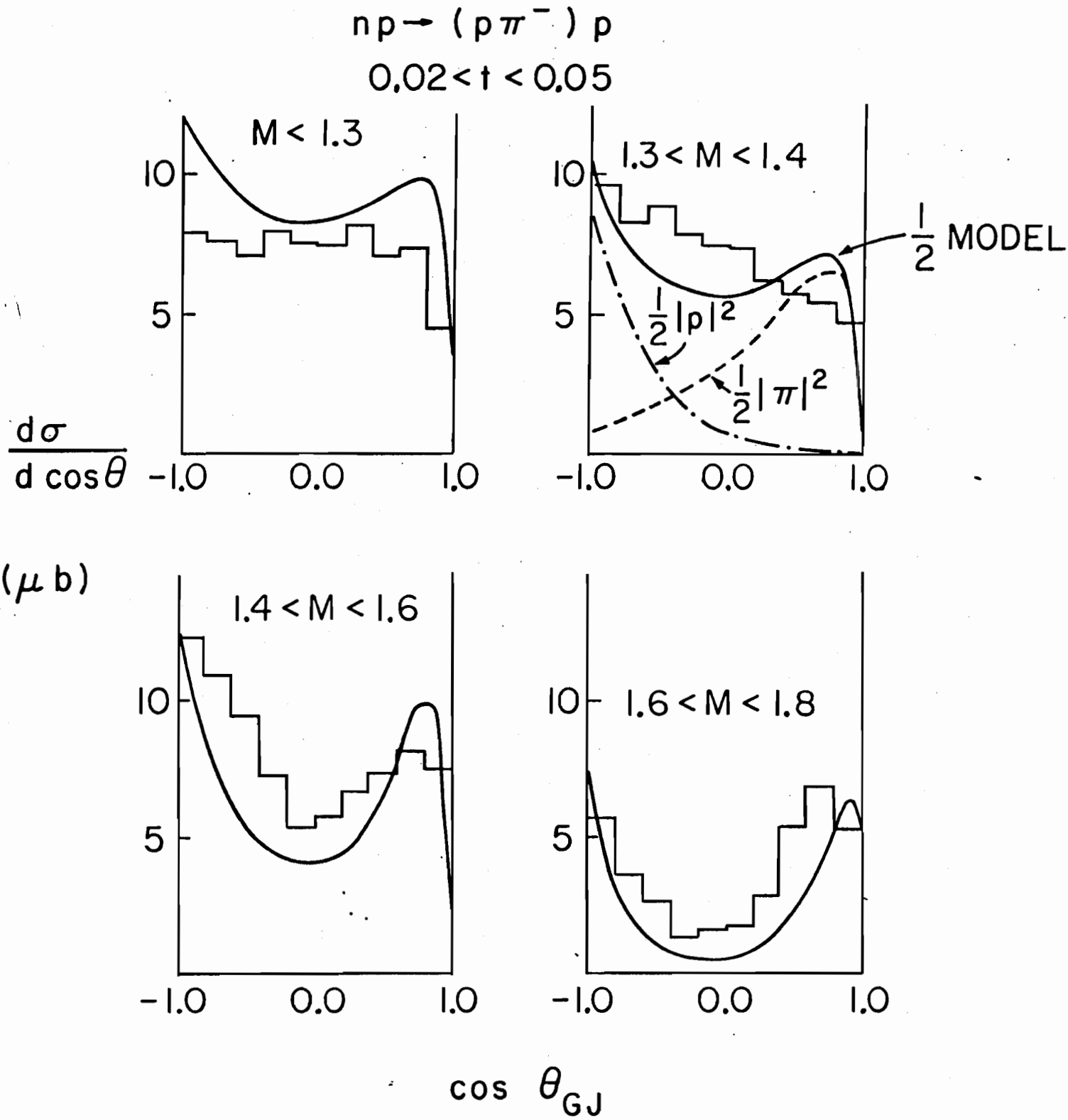


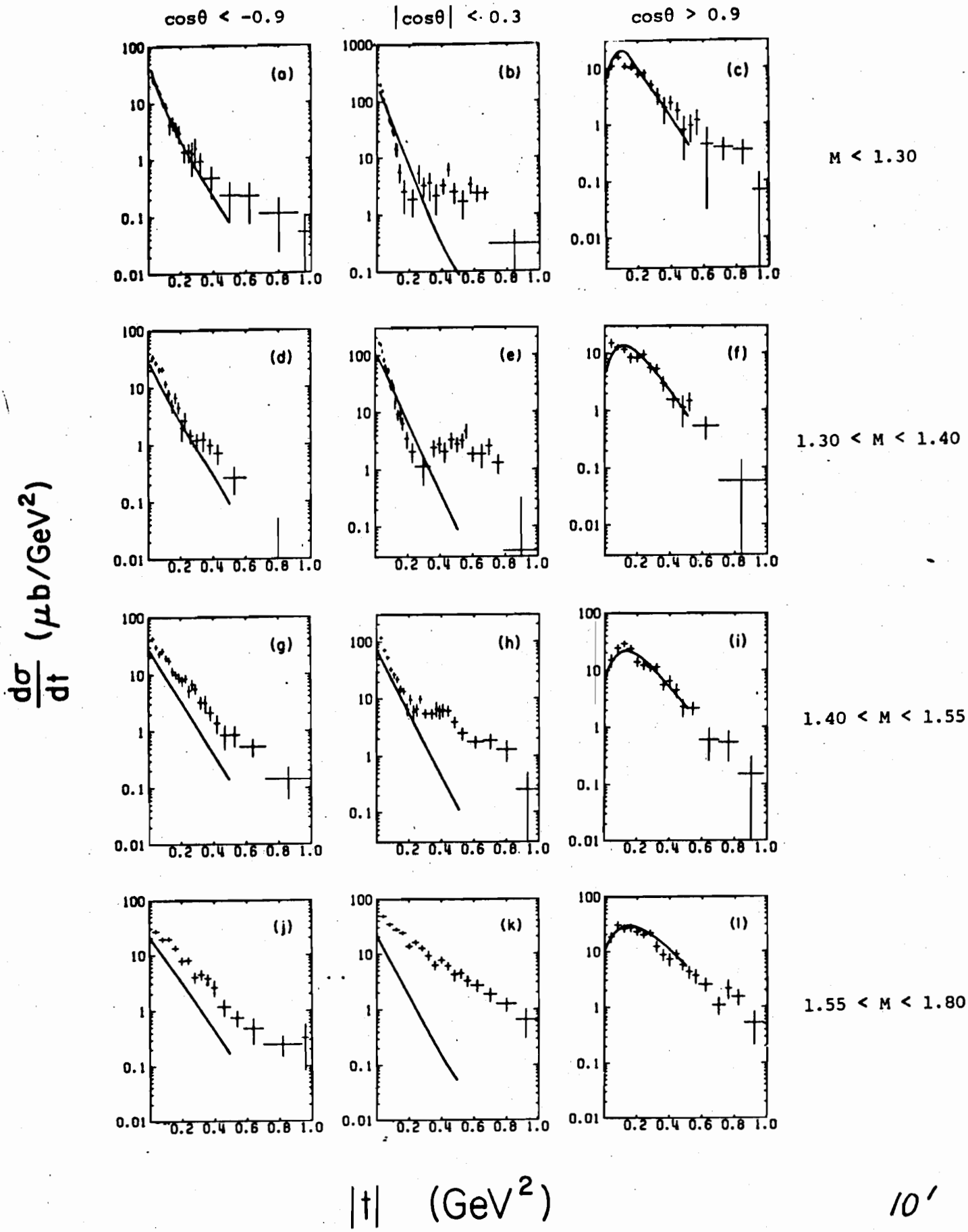
(b) proton exchange Deck



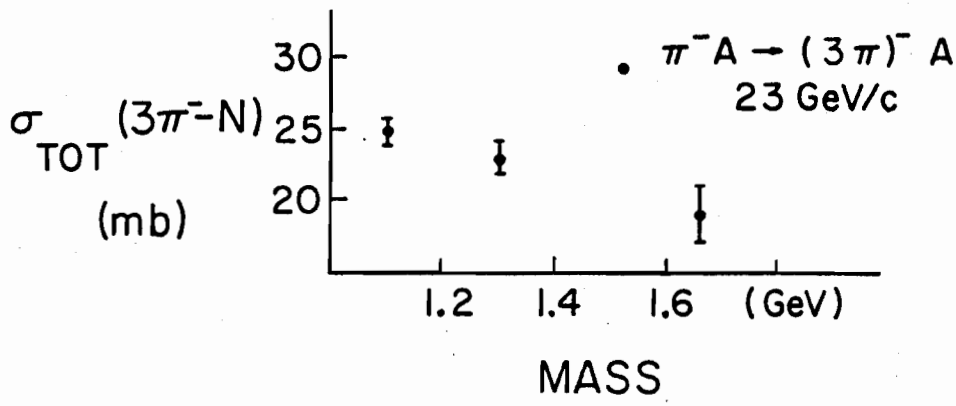
(c) direct production

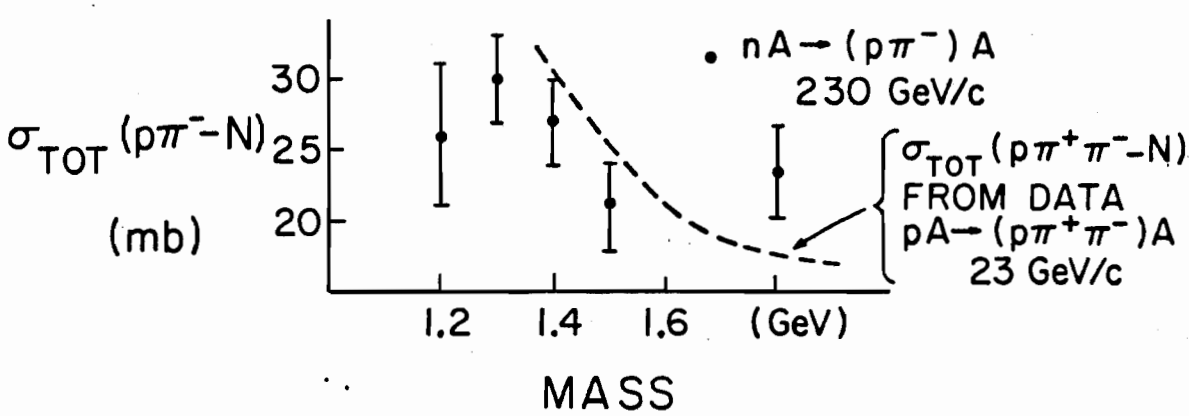


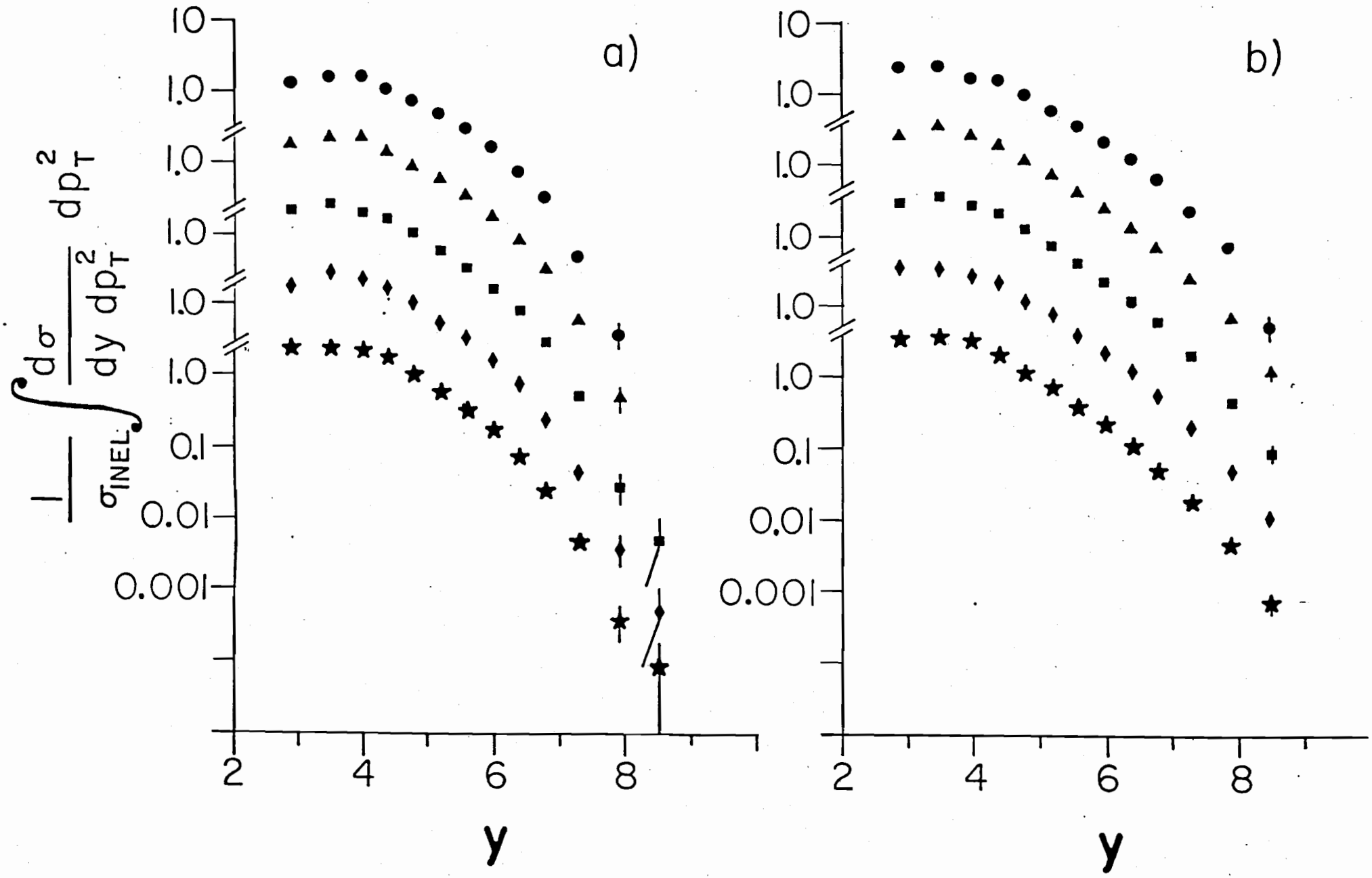

np → (pπ⁻) p
0.02 < t < 0.05
M < 1.3
1.3 < M < 1.4
1.4 < M < 1.6
1.6 < M < 1.8
1/2 MODEL
1/2 |p|²
1/2 |π|²
dσ / d cos θ
(μb)
10
5
-1.0
0.0
1.0
cos θ_GJ

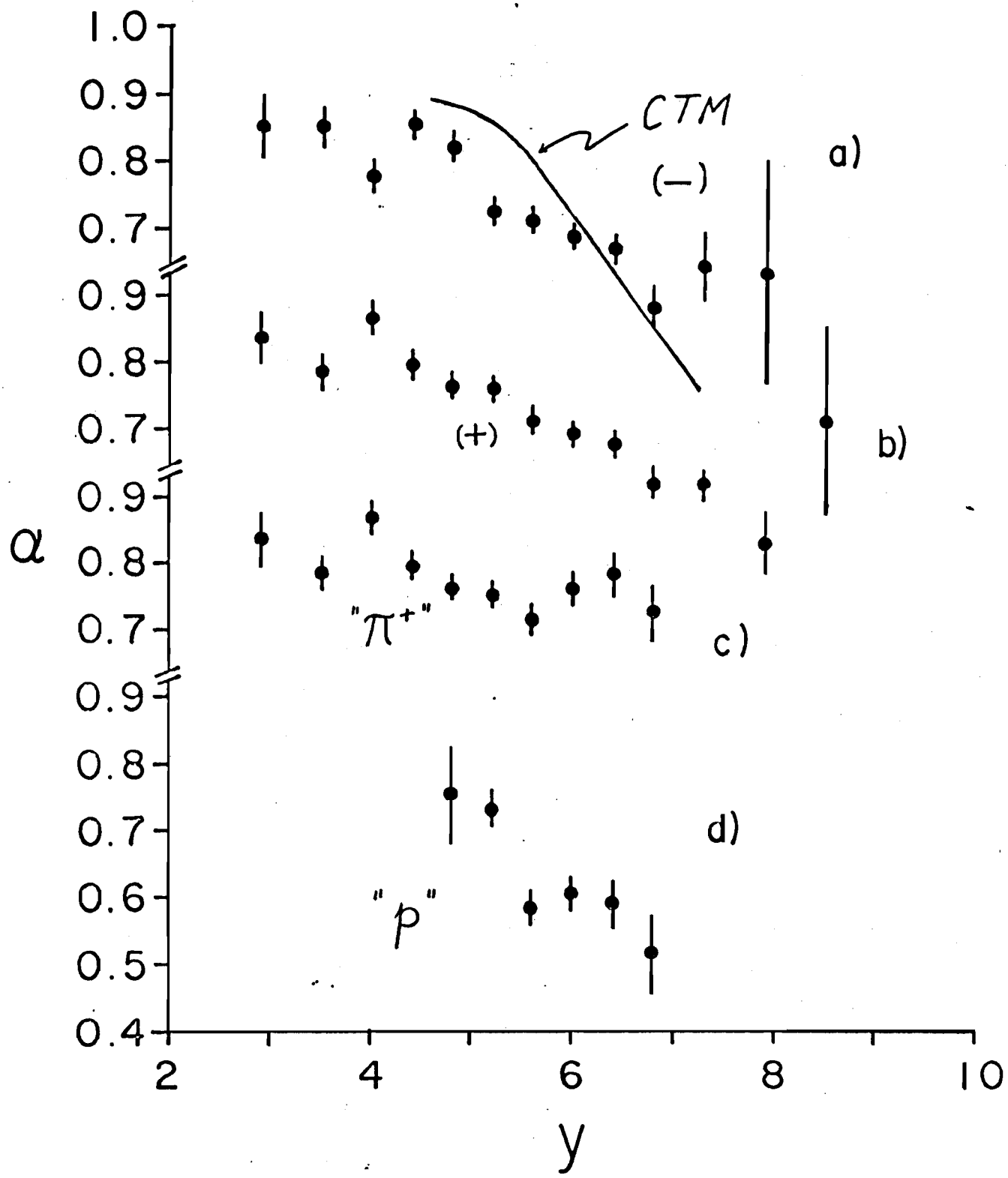

cosθ < -0.9
|cosθ| < 0.3
cosθ > 0.9
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
M < 1.30
1.30 < M < 1.40
1.40 < M < 1.55
1.55 < M < 1.80
dσ/dt (μb/GeV²)
|t| (GeV²)

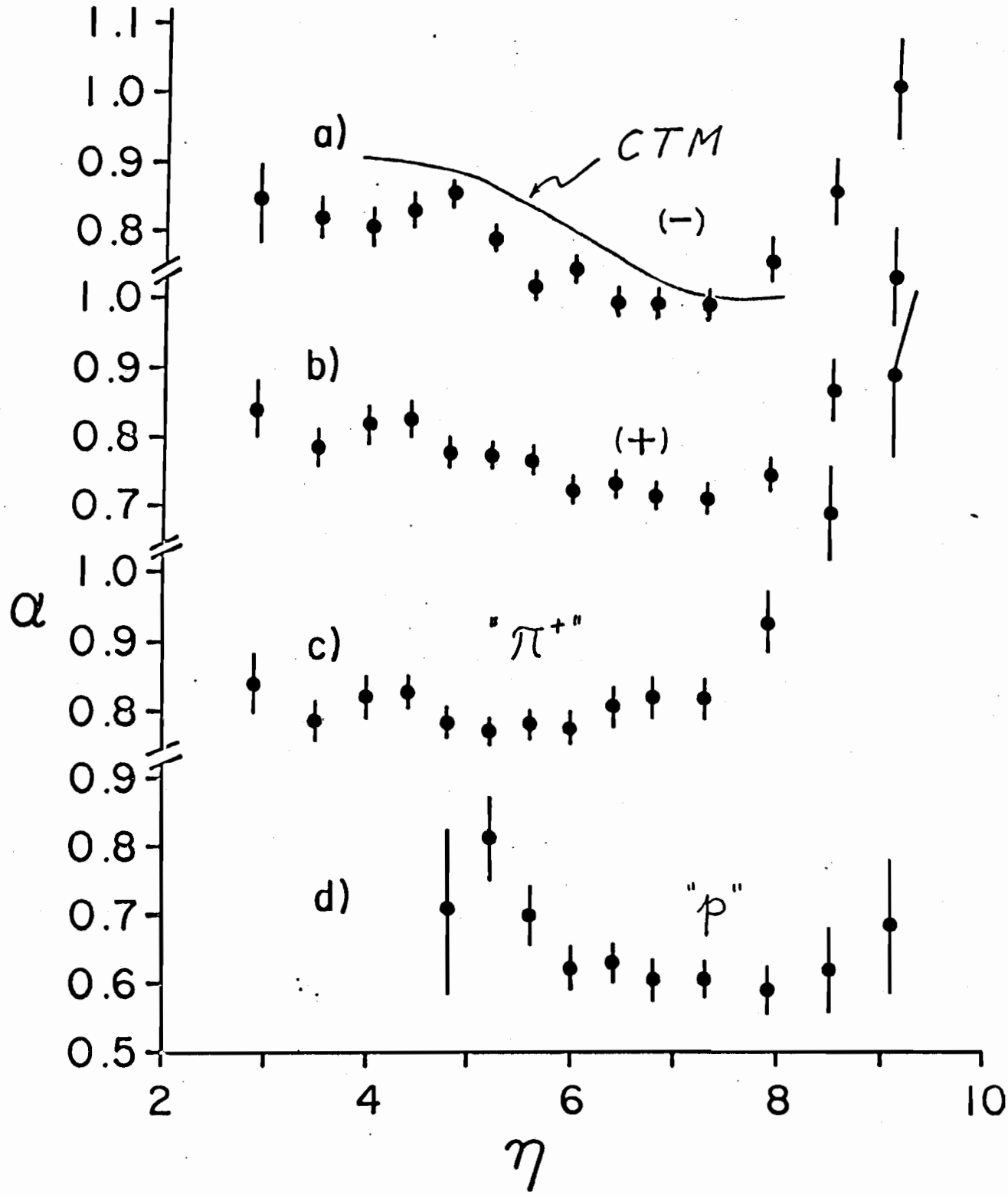
10′

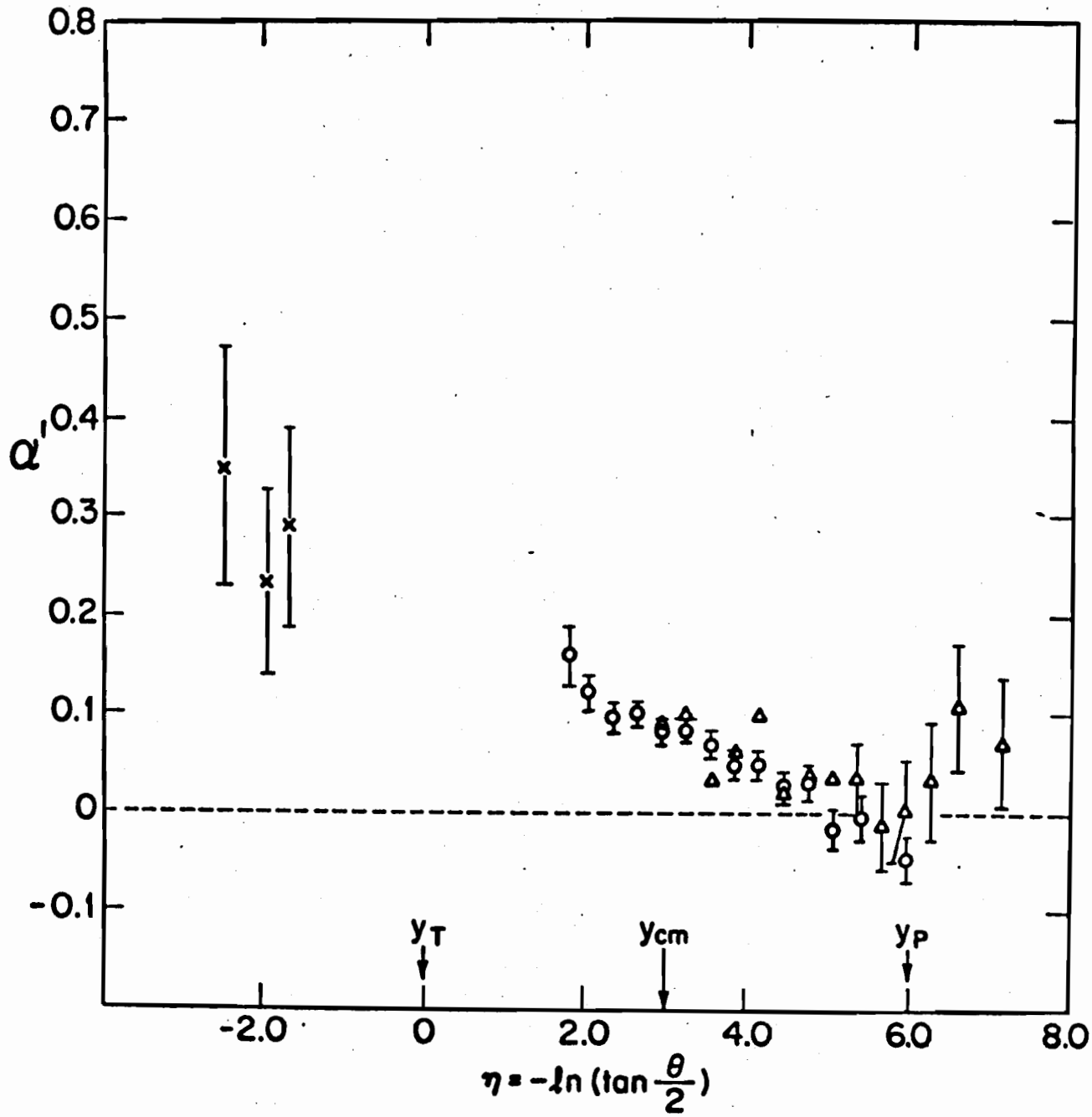

$\sigma_{TOT}(3\pi^- - N)$
(mb)
30
25
20
$\pi^- A \to (3\pi)^- A$
23 GeV/c
1.2
1.4
1.6
(GeV)
MASS

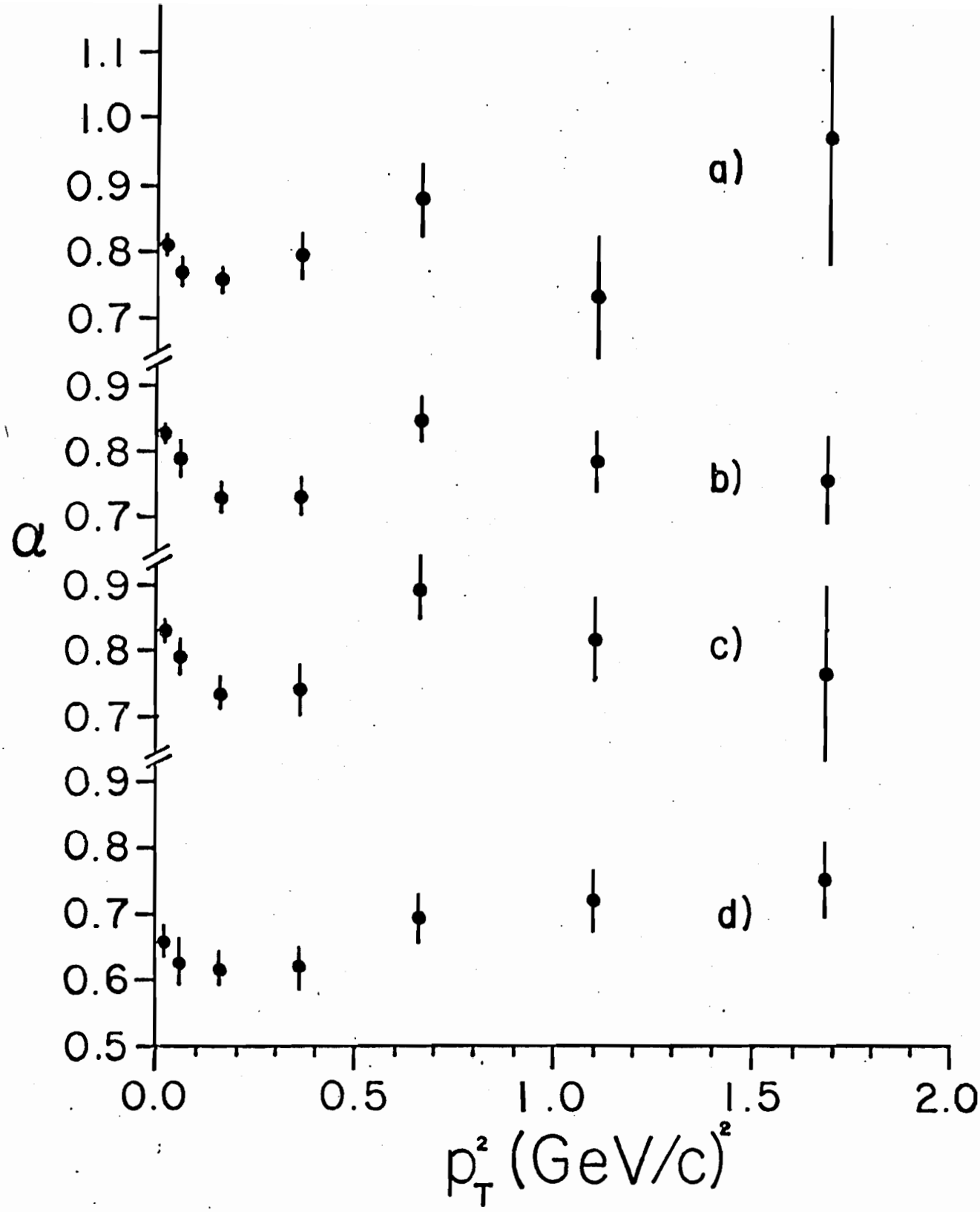

$\sigma_{TOT}(p\pi^- - N)$
(mb)
30
25
20
$nA \to (p\pi^-) A$
230 GeV/c
$\sigma_{TOT}(p\pi^+\pi^- - N)$
FROM DATA
$pA \to (p\pi^+\pi^-)A$
23 GeV/c
1.2
1.4
1.6
(GeV)
MASS

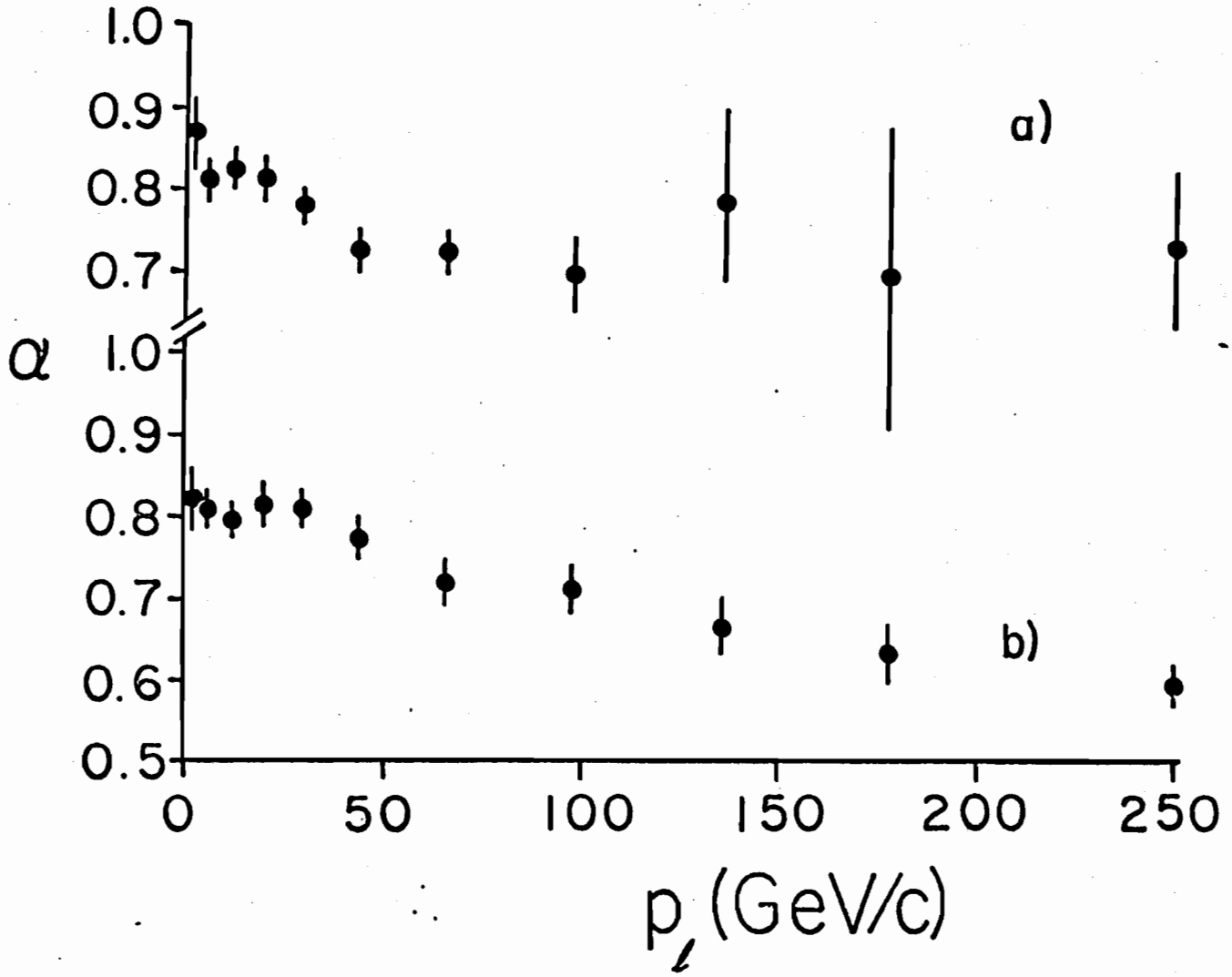

a)
b)
$\frac{1}{\sigma_{INEL}} \int \frac{d\sigma}{dy\, dp_T^2} dp_T^2$
10
1.0
1.0
1.0
1.0
1.0
0.1
0.01
0.001
2
4
6
8
y


1.0
0.9
0.8
0.7
0.9
0.8
0.7
0.9
0.8
0.7
0.9
0.8
0.7
0.6
0.5
0.4
α
CTM
(−)
a)
(+)
b)
"π+"
c)
d)
"p"
2
4
6
8
10
y

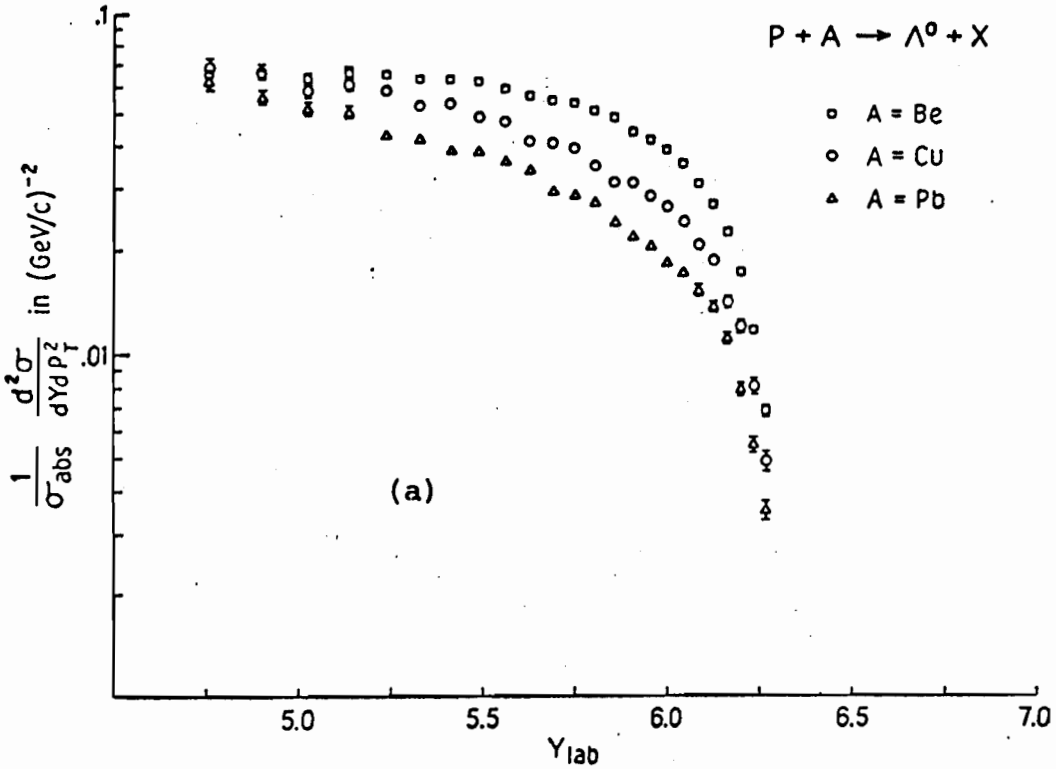

1.1
1.0
0.9
0.8
a)
CTM
(−)
1.0
0.9
0.8
0.7
b)
(+)
1.0
0.9
0.8
c)
"π+"
0.9
0.8
0.7
0.6
0.5
d)
"p"
α
2
4
6
8
10
η

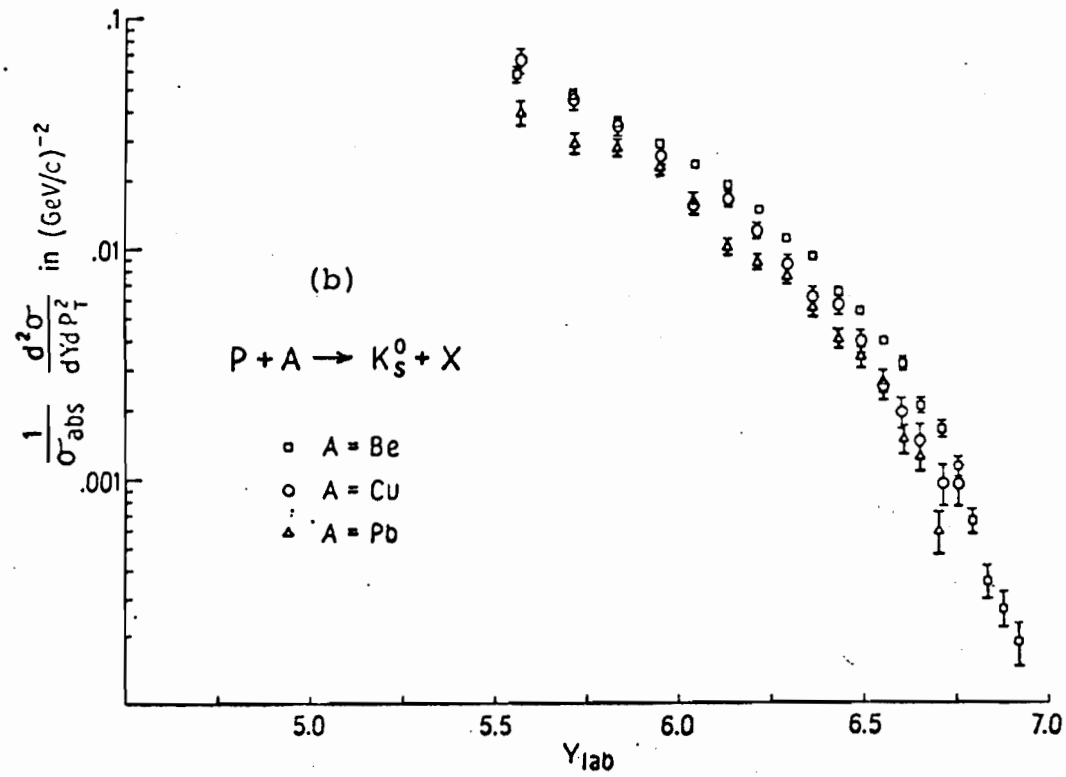

0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
α'
y_T
y_{cm}
y_P
-2.0
0
2.0
4.0
6.0
8.0
$\eta = -\ln(\tan\frac{\theta}{2})$


1.1
1.0
0.9
0.8
0.7
0.9
0.8
0.7
0.9
0.8
0.7
0.9
0.8
0.7
0.6
0.5
α
a)
b)
c)
d)
0.0
0.5
1.0
1.5
2.0
p_T^2 (GeV/c)^2

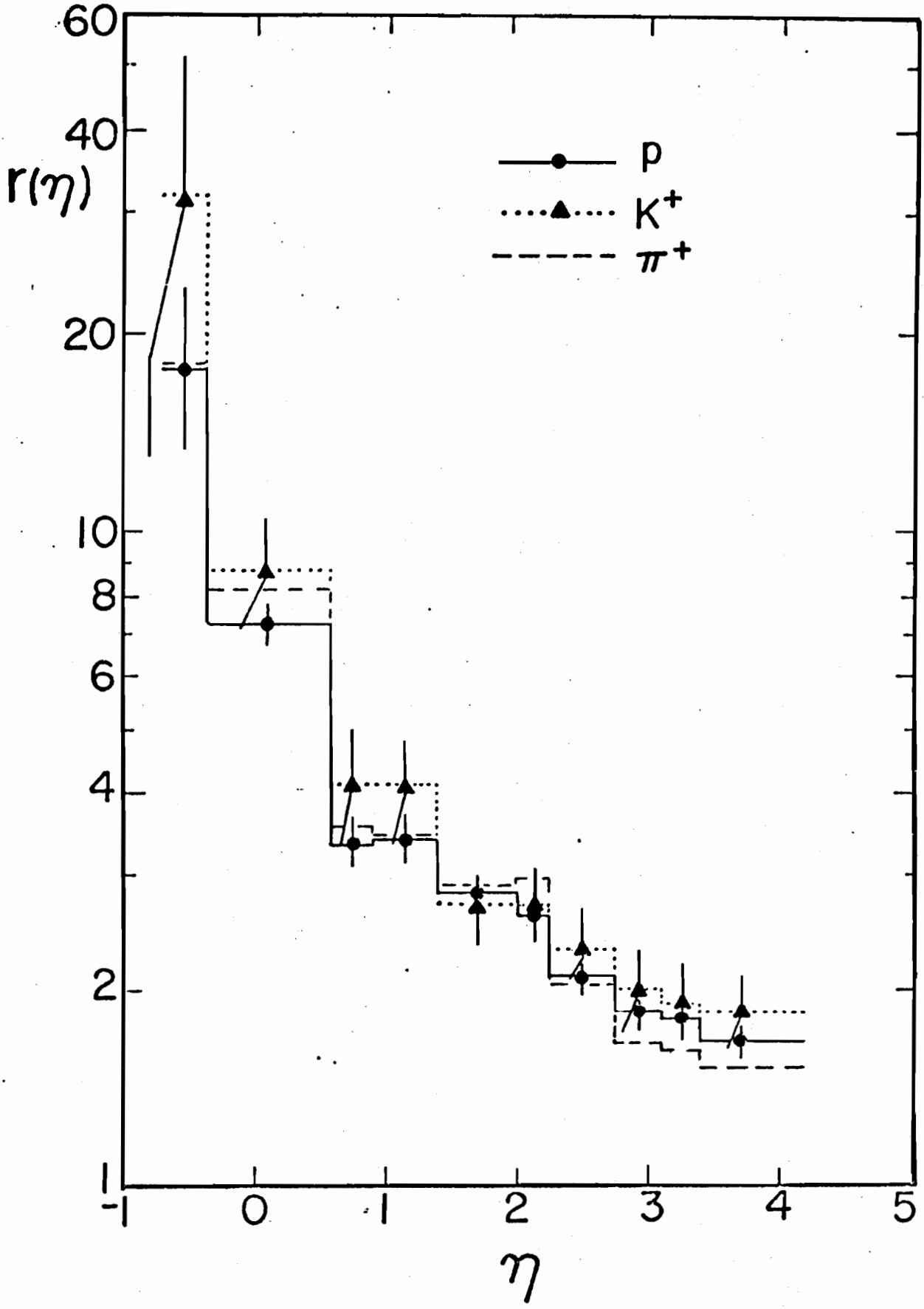


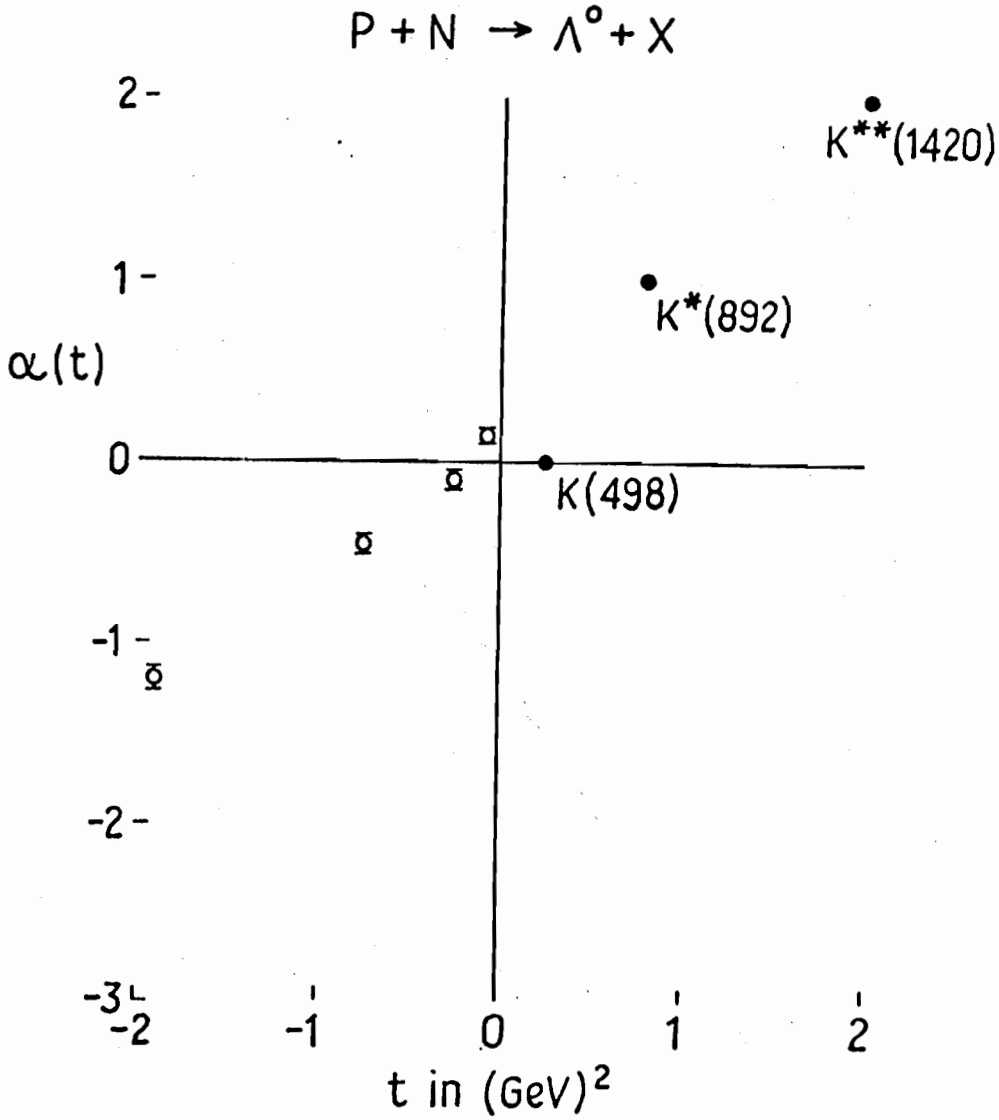
15'





Double differential multiplicity versus laboratory rapidity for (a) Λ^0 and (b) K^0_S production.


60
40
20
10
8
6
4
2
1
r(η)
p
K+
π+
-1
0
1
2
3
4
5
η



α_i parameters for fits to the invariant cross section extrapolated to A=1.