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Particle Physics and the SLAC Linac: 1962-1982

J.D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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I. INTRODUCTION

We are here to celebrate SLAC and its accomplishments. While it is my role here to review the linac program, it is hardly appropriate — or within my competence — to present a full scholarly history. In not doing so, I risk making errors of omission, and not mentioning many fine accomplishments. I apologize in advance. Also, the matter of apportionment of credits among groups and individuals is always a delicate issue. I have chosen cowardice, and cloak this review in veils of anonymity: for the most part, the contributions will not be labeled.

I will divide this history into three parts: (1) Early Days (1962-1967), (2) the Prerevolutionary Period (1967-1974), and (3) the Postrevolutionary Period (1974-). I will not follow any strict chronology. As you will see, experiments of the late '70's may find themselves classified as "early" or "prerevolutionary." Such is the nature of things; important contemporary experiments are – and should be – done on old and venerable subjects. I will also look at the subject with more of a theorist's eye than experimentalist's. I'm sorry about that, but it's just the way I am.

II. EARLY DAYS (1962-1967)

1. The Theory

In looking back at the theory of the early 60's, the most impressive feature is that (with the exception of quantum electrodynamics, QED) there wasn't any theory. By present standards, there was only phenomenology. Of course, some of the phenomenology was rather esoteric. How many still know what a wrong-signature nonsense zero is? But local field theory – for anything other than perturbation calculations — was deeply mistrusted. The basic field equations were mathemetically meaningless, ill-defined. The connection of observables to the basic field variables was regarded as unacceptably remote. Great efforts were made to provide a logical formulation of strong and weak-interaction theory in terms only of observable quantities. One then endeavored to extract predictions based only upon general truths such as Lorentz covariance, locality or microscopic causality, positivity of the energy spectrum, and symmetry principles. The strong interactions were dominated by dispersion theory and the "bootstrap" picture of hadrons. According to this view, all hadrons were regarded as equally fundamental (or non-fundamental): "nuclear democracy." Each hadron was to be considered a composite of (possibly) itself and other hadrons, the dynamics being provided by (infinite) sets of coupled dispersion-relations. The basic observables were the set of all S-matrix elements. The study of their analytic properties also led to the study of complex angular-momentum theory and the development of the beautiful theory of Regge poles. This provided a descriptive phenomenology of high energy collisions and was to become most relevant to SLAC and other machines of comparable or higher energies.

The predominance of S-matrix theory and dispersion relations in those days is hard to appreciate now. Listen to the prophetic words of L. D. Landau who wrote,[1] ca. 1960:

"...We may introduce in the theory only the scattering amplitudes... The ψ operators which contain unobservable information must disappear from the theory. And since a Hamiltonian can be built only from ψ operators, we are driven to the conclusion that the Hamiltonian method for strong interactions is dead and must be buried, although of course with deserved honor."f1

The experimental situation which helped create this view was the discovery of the vast array of hadron resonances. These were classified by the (always ubiquitous) group theorists using SU(2) isospin, SU(3) flavor, and SU(6) spin-flavor. This led to a famous Feynman aphorism[2]: "When a new particle or a new fact is discovered, I notice that all the theorists do one of two things: they either form a group, or disperse."

While the S-matrix ideology of analyticity and unitarity held together and greatly advanced the phenomenology, the group-theory classifications inexorably led to the introduction of the quark model. Quarks in this period tended to be useful mnemonic devices to easily do the mathematics. They were sufficiently bizarre that — despite the existence of a small community of theorists working on "literal" quark-models — the quarks were not widely trusted as real live constituents of hadrons. Here, for example, is Gell-Mann[3] in 1966:

"Even if there are light, real quarks, and the threshold comes from a very high (potential) barrier, the idea that mesons and baryons are made primarily of quarks is difficult to believe because we know that, in the sense of dispersion theory, they are mostly, if not entirely, made up out of one another."

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f1)

In fairness, when considering the whole context from which that excerpt is drawn, I would guess that had Landau lived to see the renormalization of gauge theories, he might well have himself discovered "asymptotic freedom" and immediately reversed his opinion.

Again, from the pragmatist Lipkin[4] in 1967:

"Quarks and symmetries are very interesting, but nobody really knows why. The secret may be deep in the mysteries of the irreproducible representations of the noncompact conspirators, supercovariant daughters, fixed Poles, moving Italians, and crazy Americans. However, I prefer to think that the mysteries will be unraveled by experiment."

Weak interaction theory was in no better shape. The nonrenormalizable Fermi coupling was (and still is) unmanageable at a fundamental level. But weak-interaction phenomenology progressed rapidly, with growing confidence in the Cabibbo theory. In addition, the emphasis on observables produced current algebra, which beautifully linked electromagnetic and weak S-matrix elements with strong-interaction symmetries. This provided a rock-solid foundation upon which discussion of strong-interaction symmetry could be based. Furthermore, the notion of spontaneously broken chiral symmetry ("PCAC") also emerged, and together with current algebra provided insights into strong interaction dynamics. This was to become a major pathway toward the notion of point-like constituents within hadrons. Indeed, dispersion theory and current algebra have played a role in understanding hadrons quite parallel to Kramers dispersion-relations and Heisenberg matrix-mechanics in understanding atoms.

2. Experiment

Given such a world-view, how did the SLAC linac fit in? In the early 1960's, it didn't. The fit, at best, looked awkward. I recall a distinguished colleague, when hearing of my intention of joining SLAC, asking "Aren't you afraid SLAC will turn out to be a white elephant?" I frankly hadn't thought about that. All I knew was that SLAC had Pief and a lot of good people. But from the context I described, the zoo of hadron resonances were obviously best studied at proton machines. And weak decays were best studied in the intense secondary beams produced in (good duty-cycle) proton machines. Likewise proton machines were projected to produce the best neutrino beams. What was left for SLAC? A superb electron beam, very intense photon beams, and a muon beam of good quality (brightness) — but all with very poor duty cycle, making coincidence experiments very difficult. Was this really enough, especially with Cornell and DESY electron synchrotrons providing rather direct competition??

The SLAC heritage was of course Mark III; espcially the elastic electron scattering measurements of nuclei and nucleons. Elastic form factors could be measured at SLAC to large Q^2. The form-factors of the Δ resonance and of higher resonances became easily accessible at SLAC energies. What we call today the "deep continuum" was recognized as of potential interest, but it was very unclear how to handle it theoretically,[f2]

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f2)

Inelastic electron scattering from nuclei was known to give direct information of constituent structure of nuclei, and was well-studied within the Stanford theoretical community. I recall Leonard Schiff, while participating in the first Stanford Physics Department colloquium on "Project M", underlining the importance of inelastic electron scattering from the proton as giving information on the instantaneous charge distribution of its constituents. He emphasized that "the Monster" was high enough energy to do so.

One of the early experimental results was the (approximate) verification of the "dipole formula" for the elastic nucleon form factors. In those days of dispersion relations, predictions ranged from the "natural" Q^{-2} falloff to the "fastest possible" exp(-Q). Theoretical (and experimental) haberdashers provided many fits. But the observed (Figs. 1-2) Q^{-4} behavior languished for many years until being interpreted via quantum chromodynamics (QCD) and quarks.

Positron-proton and electron-proton interactions were compared, and dispelled whatever fears existed that QED failed or that radiative corrections were large. Muon-proton elastic scattering was likewise measured and, within a small but nagging normalization discrepancy, agreed with muon-electron universality and QED.

Higher resonances were seen and form factors measured (Figs. 3-4). But even after much coincidence work at DESY, that topic never really took hold among a broad community. The behavior of such form factors, however beautifully measured, has for a long time become overshadowed by the studies of the continuum. As QCD spectroscopists become more sophisticated and look at finer details of excited nucleon states, they should find these measurements a delight.

Less well-anticipated in the early days was the ultimate SLAC contribution to strong interactions. However, by the time that the machine was ready for physics in 1967 there already were signs of change. The predominant theme was "vector-dominance" (VD). This was the notion that at high energy the photon can, for purposes of studying its interaction with hadrons, be considered mostly ρ^0 with small admixture of ϕ and ω (the famous 9:2:1 ratio), and perhaps a little more. Shortly after its introduction, VD spread everywhere, from electromagnetic form factors to all high energy photon-induced processes to neutrino reactions. Eminent theorists codified the concept in the elegant language of field-current identities. Thus VD entered the theoretical formalism at a quite fundamental level and influenced the development of current algebra. Within a factor 2 accuracy, the idea works experimentally, and the study of π and ρ photoproduction entered the province of pure hadron physics.

The total photon-nucleon cross-section, when measured (Fig. 5), looked remarkably similar to the π-nucleon cross-section. ρ^0 photoproduction became the analogue of elastic π-nucleon scattering and was extensively studied, both on nucleons and nuclei. I am hard put to summarize succinctly the plethora of measurements (not to mention the hot controversies). I have chosen an especially pretty measurement showing the polarization of outgoing ρ^0 tracking, as expected, very well the polarization of incident photon (Fig. 6). It should be mentioned that photon polarization at SLAC was produced by instrumental gems — in one case a ruby laser, in another a diamond crystal.

Another series of measurements relevant to VD as well as to strong-interaction Regge theory was single-π and single-K photoproduction. At one point, strong-interaction Regge theory was at least as well-served by this series of measurements as by purely hadronic processes. As the sophistication of theoretical analysis grew, the interpretations became complicated: gauge-invariance, "Regge cuts," absorption corrections seem important. I frankly don't know where the theory of pion photoproduction ended up. But the data (Figs. 7-8) are beautiful.

An additional community of strong-interaction physics built up around the bubble chambers. Those studies, made by a very diverse experimental community, are not easy to briefly summarize. But I think one of the most significant experimental achievements of the late 1960's and early 1970's was the quite exhaustive (and exhausting) study of hadron resonances – especially baryon resonances. This was an accomplishment of a very large number of people doing a large number of experiments (not all, of course, at SLAC) and phase-shift analyses on π-nucleon elastic and inelastic scattering. The output was a collection of "pigs' tails" (Fig. 9 shows a small sample) or Argand plots. When put together they gave an impressive spectroscopy which, no matter how much it grew, still was readily interpreted within the quark model. Properties of dozens of resonances were succinctly summarized in the phrase "$\underline{56}$, L even; $\underline{70}$, L odd." Certainly, a major reason for the growth of confidence in the quark idea during the early 1970's was this impressive body of evidence.

Meson spectroscopy remained at that time more confused. But there has been steady progress in the last few years. At SLAC many excited K* states have been found; they now appear to fall into a reasonably orderly quark-model picture (Fig. 10). I doubt that in the early days anyone would have anticipated such rich and long-lasting contributions to pure hadron physics.

With regard to weak interactions, the most important contributions from the early days were in the field of CP violation. One of the more pleasant features of the SLAC secondary beams turned out to be a relatively neutron-free K_L beam. The CP violation parameters were beautifully measured: the charge-asymmetry in $K_{\ell 3}$ decay as well as the

$K_{\pi 2}$ amplitude η_{+-}. And subsequent measurements (Fig. 11) cleared up confusion in the CP-conserving $K_{\ell 3}$ parameters as well, and helped to increase confidence in the Cabibbo picture of weak interactions.

Tests of QED on the linac turned out to be rather minimal; I only recall the $e^+p/e^-p/\mu^\pm p$ comparisons and checks that the "Rosenbluth formula" worked. In the long run, probably the best QED test became the simple scaling description of deep-inelastic scattering — hard to comprehend were QED to have broken down.

III. THE PREREVOLUTIONARY PERIOD (1967-1974)

1. Theory

During this period evolved our present-day theory, the "standard model." Not everyone took note, including myself. Even some of the inventors were slow. The origins of the weak-interaction model as we know it now date to 1967-1970. The strong-interaction QCD theory evolved from 1972-1974. In my opinion, the most important turning point was the success in ~1971 of proving renormalizability of non-abelian gauge theories. That event galvanized theorists into taking such theories very seriously. Prior to this development there was plenty of reason to do so on aesthetic grounds, but no way to enter the world of real calculations.

This period also witnessed the full emergence of quarks as hadron constituents. Not only was this an outgrowth of the spectroscopy, but also of course of the series of SLAC inelastic electron scattering experiments. But before looking at the experimental side and while talking about theory, one may see this need for local constituents emerging from current algebra sum-rules analogous to various sum-rules used in atomic and nuclear physics. In the early 1960's, the most popular sum-rules were roughly analogous to the "dipole" sum-rules of atomic physics — designed for long-wavelength, low energy applications. Local versions, based on commutation relations of current densities, emerged in the late 1960's. More microscopic information about hadrons (e.g. their high energy excitation) was obtainable. And a theoretical response to the experimental challenges associated with the new high energy probes, notably the SLAC leptons and the neutrinos from proton machines, was needed.

These local sum rules were most easily applied to neutrino processes. But electrons and muons could be implicated via the close (CVC) connection between weak and electromagnetic currents. This turned out to be in itself quite sufficient for revealing what was going on.

The atomic and nuclear analogues of the current-algebra sum rules directly express information about constituents of atoms and nuclei. Why any problem for this repeat of history? The problem was one of relativity. In those days it was not possible to tinker with models explicitly violating Lorentz-covariance and/or microcausality the way people sometimes do nowadays. It took a while to fully recognize that the elements of simplicity lay not in a non-relativistic picture but rather one of extreme-relativistic motion.

The existing concepts of strong-interaction physics also served to shape the theoretical picture of deep inelastic scattering. The region of high energy and moderate Q^2 (small x) was (and still is) best described in the language of Regge-poles, while the large-x region was described by ideas of duality: the deep continuum and resonance region are intimately related. The idea of duality evolved within strong interactions into a powerful tool relating Regge-behavior to resonance spectroscopy. The notions of linear Regge trajectories and string models became prevalent and were the precursors of the linear quark-antiquark potentials of QCD.

In the midst of all this came the partons, pointlike hadron constituents with obscure dynamics. They rested uncomfortably, almost incompatibly, with both the S-matrix ideology and with field theory. But they expressed the content of most of the above ideas in very simple terms, and for unsophisticated folk they provided some welcome, if only temporary, relief from the arcane theoretical formalism of current algebra, Regge-poles and the like. However, it would not be long before everyone would be discussing the anomalous dimension of the third Nachtmann moment.

From 1971-1974, the revival of local Lagrangian field theory concepts gained momentum. The theoretical discovery that at short distances QCD became a weak-coupling theory ("asymptotic freedom") propelled that theory forward. And the experimental discovery of neutral-current weak interactions propelled the electroweak gauge theories forward to the point that, by the eve of the November Revolution, charm was being demanded by many theorists as the only way to save the theory.

By the way, neutral currents were not only seen at proton machines. Fig. 12 shows an excellent candidate from the first SLAC "beam dump" experiment. It caused much excitement at the time. But subsequent runs did not turn up more unambiguous candidates.

2. Experiment

The central prerevolutionary experimental results were of course the beautiful series of deep-inelastic electron scattering measurements. The evolution of these experiments spanned the entire prerevolutionary period. Beforehand there was great anxiety about radiative corrections. The (conservative) assumption was made that the inelastic cross-section $\sigma_{T,L}(s,Q^2)$ fell with Q^2 in proportion to the elastic cross-section. This led to an enormous "radiative tail" (Fig. 13) that threatened to swamp any signal. It took a while for the experimentalists to convince themselves that what was seen was real and not an artifact (Fig. 14). The first scaling curve (Fig. 15) appeared in 1968. More beautiful versions (Fig. 16) soon followed. It was not immediately obvious that such a dull curve contained news about point quarks. Maybe it was all to be explained by "diffractive" Pomeranchuk-Regge-trajectory exchange. If so, electron-neutron scattering should equal electron-proton scattering. It was not so (Fig. 17). Maybe the data could be explained by VD; if so, the longitudinal cross-section σ_L should greatly exceed σ_T. It was not so (Fig. 18). Finally, for pointlike constituents the polarization asymmetry should be large. An exquisite series of experiments, utilizing both an intense polarized beam and a polarized target, revealed that the asymmetry is remarkably large (Fig. 19).

Scaling behavior was soon followed by observation of scaling violations. Theorists responded by twisting the definition of the scaling variable and refitting to new scaling variables. Nowadays the theory has unwound, and scaling violations which survive such redefinitions are associated with QCD "radiative corrections."

Meanwhile, similar results were seen in high energy neutrino reactions. By the time of the weak neutral-current discoveries, the parton and scaling ideas were well enough developed to make easier the job of extracting the basic parameters.

Another major prerevolutionary program consisted in exploration of the hadron final state in these deep-inelastic processes. If a contituent quark were really hit so hard by the electron, did it come out? No, that was not expected and not found. Would these violent, high Q^2 processes lead to a final state of radically different character? Such speculations existed, but parton ideology suggested the opposite: at fixed total available center-of-mass energy W there should be little if any difference from ordinary processes. SLAC experiments, in the original muon beam and in the streamer chamber and bubble chamber, were carried out and were among the first to show (Figs. 20-21) that the final-state structure for virtual photo-production was almost indistinguishable from real photoproduction. This might not have been satisfying to experimentalists, who tend to enjoy spectacle. But the result was especially significant to parton theorists, who felt it greatly increased the odds that high-p_T quark jets would be visible in e^+e^- annihilation and in hadron-hadron collisions.

IV. POSTREVOLUTIONARY DEVELOPMENTS (1974-)

1. Theory

By the eve of the November Revolution, suspicions of local field theory for strong and weak interactions were being dispelled. Every piece of present-day "standard-model" ideology was in place, including grand unification and proton decay. Only a small minority of theorists — perhaps only one[5] — fully accepted that ideology at the time. With hindsight, the rest of the story was just a matter of getting enough experimental evidence.

After the November Revolution the main theoretical developments were underdamped oscillations about the standard model. A good deal of the oscillation was driven by a variety of experimental false-alarms (mostly not from SLAC). These stimulants measured the elasticity of basic electroweak gauge-theory (very large), and a host of variants of the simplest model were created. QCD, on the other hand, was sufficiently nonpredictive to not have that problem, and it grew steadily in credibility. It was largely a matter of getting used to it.

The story of the "standard model" is nowadays rather familiar, so we shall not recount it again.

2. Experiment

Much of the fruits of the November Revolution emerged from SPEAR. But the linac contributed as well. For a variety of reasons, it took a while to be convinced that charm really explained the ψ. There was a question of whether ψ was in fact even a hadron. Photoproduction of ψ was a good way to find out. The SLAC spectrometers were quickly put to use and ψ was soon found (Fig. 22). Direct leptons were subsequently measured as well — most likely the decay products of mesons containing charmed quarks. Rather than showing those data, I have chosen some prerevolutionary measurements by SLAC health physicists (Fig. 23). They measured in 1973 the flux of photoproduced particles, presumably muons, emerging at large angles to the beam and penetrating $\sim$6.5 m of iron shielding. The yield is much larger than could at that time be accounted for by known processes. To my knowledge, no one yet understands the origin of this flux, but ψ and charm are prime candidates.

Study of charm at the SLAC linac continues up to the present time, where charm decays have been observed in an elegant photoproduction experiment using the rapid-cycling 40" bubble chamber and backscattered laser beam (Fig. 24).

But the most celebrated postrevolutionary linac experiment has to be the measurement of the minute electroweak polarization asymmetry in deep-inelastic electron-nucleon scattering. The experiment, five or six years in the making, succeeded not only in observing asymmetry, but in measuring it quite accurately as well. This required a new, very intense source of polarized electrons, unprecedented control of the beam down the linac and through the switchyard, and novel techniques for detecting the large flux of scattered electrons. The results were most convincing. The observed asymmetry was clearly correlated with the polarization of the source 2 miles away (Fig. 25), and with energy, because of g-2 precession of electron spin as the beam turned the corner in the switchyard (Fig. 26). And this experiment, immediately dubbed "classic," "experiment-of-the-year," etc., had the good fortune of being timely. When the results came out (Fig. 27), much (but not all) of the theoretical confusion over alternative electroweak gauge theories had died away, and there were only two or three attractive gauge-theory options left. The experiment ruled decisively in favor of the "standard" electroweak model.

V. SUMMARY AND PROGNOSIS

1. Theory

Where do we now stand in the light of the history we have recounted? The old language may sound strange to young ears. If all goes well in the future with the standard model (or something else not too dissimilar), what is the relevance of all those old ideas of dispersion theory, Regge poles, and current algebra? I suspect there will be a renewed appreciation. As QCD theory progresses, attention should increasingly turn away from the easy "hard" processes (the next generation will replace "easy" with "trivial") and the "simple" nonpertubative problems such as calculation of the proton mass. Attention may swing back to more dynamical and structural issues such as the pattern of excited states. (Already one sees some connection of Regge-trajectory slopes with the slope of the linear part of the charmonium potential). And already the interplay of QCD and chiral symmetry is under intense study.

Old problems are being studied with renewed intensity. The proton elastic form factor is a prime example: can the quark-QCD ideas and data be reconciled? To first approximation, the answer seems to be yes. The connection of Regge phenomenology with QCD needs attention. Even the Regge limit of electroproduction and neutrino structure functions (especially "nonsinglet") is not at all accountable from QCD first principles.

Nowadays it is hardly respectable to talk about any hadronic phenomenon without mentioning quarks, gluons, and QCD. It's not at all like the early days. Again, recall the analogy with the early days of atomic physics. Heisenberg's matrix "observables" became "replaced" by the abstract, albeit convenient, Schrödinger wave function. For hadrons, the S-matrix is now being "replaced" by something else more abstract — but as yet ill-defined. But I think in the long run something like the old language will emerge again in describing phenomena in the domain of non-perturbative QCD. Why? Because there is simply no justification in using quark-gluon language for large distance phenomena. The old language was built from solid foundations. Those foundations are as solid today as they were in the early days.

But in any event, the last two decades have been extraordinarily fruitful. There is renewed confidence in field theory, along with excellent candidate theories of strong and electroweak forces. There is insight into the substructure of hadrons and a tidy, albeit mysterious, "periodic table" of basic constituents of matter. No one in the early days could have expected so much to happen so quickly.

The next step is to see whether the "standard model," far from proven at present, is really right. The SLC collider should contribute greatly to answering that question.

2. Experiment

The evolution of the SLAC linac has been something like that of any large community. First comes the building of the inner city. Then after the initial flourishing, there is movement to the suburbs (I count 4 or 5). Still later comes the exurban movement (one or two??). But the source of prosperity still remains at the center.

Is there a future for inner-city physics? What is left for the conventional linac (other than SLC) to do? There is still the possibility for exploratory work — for example the beam-dump experiment now in progress (although that one is almost "suburban"). Higher energies will be very useful for charm photoproduction experiments. And nowhere else can one do deep-inelastic structure function measurements at large x as well as at SLAC. Scaling violations, σ_L/σ_T, and A dependence studies at large x and Q^2 will deserve new rounds of measurements. It is also likely, of course, that the most interesting future measurement on the SLAC linac will be "none of the above."

And what is the lesson that can be drawn from this brief retrospective? Certainly the SLAC linac has been no white elephant. And what made the big difference? It has been a good director, a good staff, good funding, good engineers and technical support, good experimentalists, a good theory group, simply lots of very good people — and a little good luck as well. With SLAC heading for its (N+5)th anniversary as healthy and vital as ever, all I can add is — good luck!

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FIGURE CAPTIONS

1. SLAC measurements of the elastic form factor of the proton, exhibiting the approximate fit to the "dipole formula." From P. Kirk <u>et. al.</u>, Phys. Rev. <u>D8</u>, 63 (1973).
2. Deviations from the "dipole formula." P. Kirk, et. al., <u>op</u>. cit. (Fig. 1).
3. Spectrum of inelastically scattered electrons showing the higher resonances. From E. Bloom <u>et. al.</u>, SLAC-PUB 796, submitted to the 15th International Conference on High Energy Physics, Kiev, USSR, 1970.
4. Spectrum of scattered electrons at 4^0 and various energies. Despite emergence of the deep continuum, the ratio of resonance signal to background does not significantly change as energy increases ("duality"). From E. Bloom et. al., <u>op. cit.</u> (Fig. 3).
5. Total photon-nuclear cross-section, as measured by various groups.
6. Angular asymmetry in the photoproduction of ρ^0. ψ_H is essentially the angle between the plane of the dipion and the plane of linear polarization of the incident photon. From J. Ballam et. al., Phys. Rev. <u>D7</u>, 3150 (1973).
7. Early counter data on single-pion photoproduction and the "inverse" process $\pi^- p \rightarrow \rho^0 n$ illustrating the variety of polarization and asymmetry measurements used to test vector dominance:
   a. Unpolarized cross-section.
   b. "Natural-parity" cross-section.

c. "Unnatural parity" cross-section.

d. Asymmetry parameter.

From F. Bulos et. al., Phys. Rev. Letters 26, 1457 (1971).

8. Summary of cross-sections for photoproduction of pseudoscalar mesons. From R. Diebold, "Proceedings of the 1969 High Energy Physics Conference, Boulder, Colo.," p. 3 (1969).

9. Typical collection of Argand diagrams for $\pi N \to \pi\pi N$ phase-shift analyses. From A. Rosenfeld et. al., published in "Proceedings of the 17th International Conference on High Energy Physics, London, 1974, Vol. 2, p. 113.

10. Pattern of K^* excited states. Recent addition from new phase-shift analyses are shown in bold face. [D.W.G.S.Leith, private communication.]

11. Measurement of parameters of K_{e3}. The "Callan-Treiman point" tests the Cabibbo model of weak-interactions and current algebra. From G. Donaldson et. al., Phys. Rev. Letters 31, 337 (1973).

12. Photograph of a muonless neutrino event from the early running of the first SLAC "beam-dump" experiment.

13. An early estimate of the effects of radiative corrections in inelastic e-p scattering. From SLAC Proposal P-4; W.K.H.Panofsky, et. al.; "Proposals for Initial Electron Scattering Experiments Using the SLAC Spectrometer Facilities," Appendix V, Fig. 4.

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15. First evidence for deep-inelastic scaling behavior, as presented by W.K.H.Panofsky; "Proceedings of the 14th International Conference on High Energy Physics," Vienna, 1968, p. 23.

16. Typical "scaling" curves for deep-inelastic structure functions. From E. Bloom et. al., op. cit. (Fig. 3).

17. Ratio of electron-scattering from neutrons to that from protons. From A. Bodek et. al., Phys. Letts. 51B, 417 (1974).

18. Separation of structure functions W_1 and W_2, showing relatively small values of $R=\sigma_L/\sigma_T$ and clear disagreement with VD (dashed line) predictions. From R. Taylor, "Proceedings of the 4th International Symposium on Electron and Photon Interactions at High Energies," Liverpool, 1969, p. 251.

19. Parallel-antiparallel polarization asymmetry in deep inelastic scattering of polarized electrons from polarized protons.

20a. Inelastic muon scattering event from the SLAC streamer chamber.

20b. Inelastic muon scattering event from the SLAC 40" rapid cycling bubble chamber.

21. Multiplicity of muoproduced hadrons vs. Q^2 at fixed W. From J. Ballam et. al., "Proceedings of the 16th International Conference on High Energy Physics," Batavia, Illinois, 1972 (NAL 1973), vol. 2, p. 66.

22. Observation of ψ in SLAC spectrometers. From U. Camerini et. al., Phys. Rev. Letters 35, 483(1975).

23. Observations by SLAC health physicists of photoproduction of particles penetrating 6.5 m. of steel. Note the interesting units (rads/coul.) and detection technique. TLD = thermoluminescent dosimeter, as carried around by SLAC employees in their ID cards.

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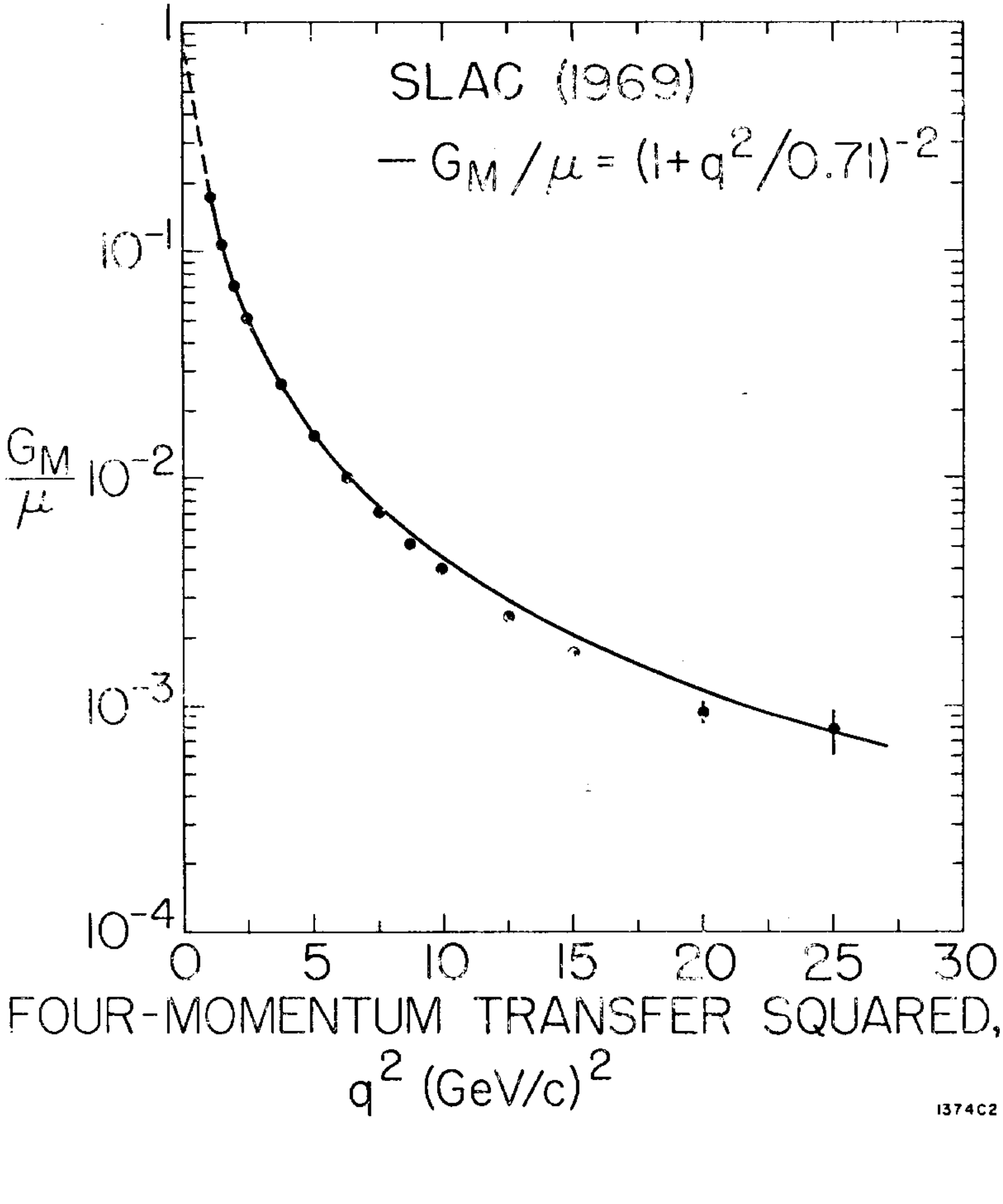
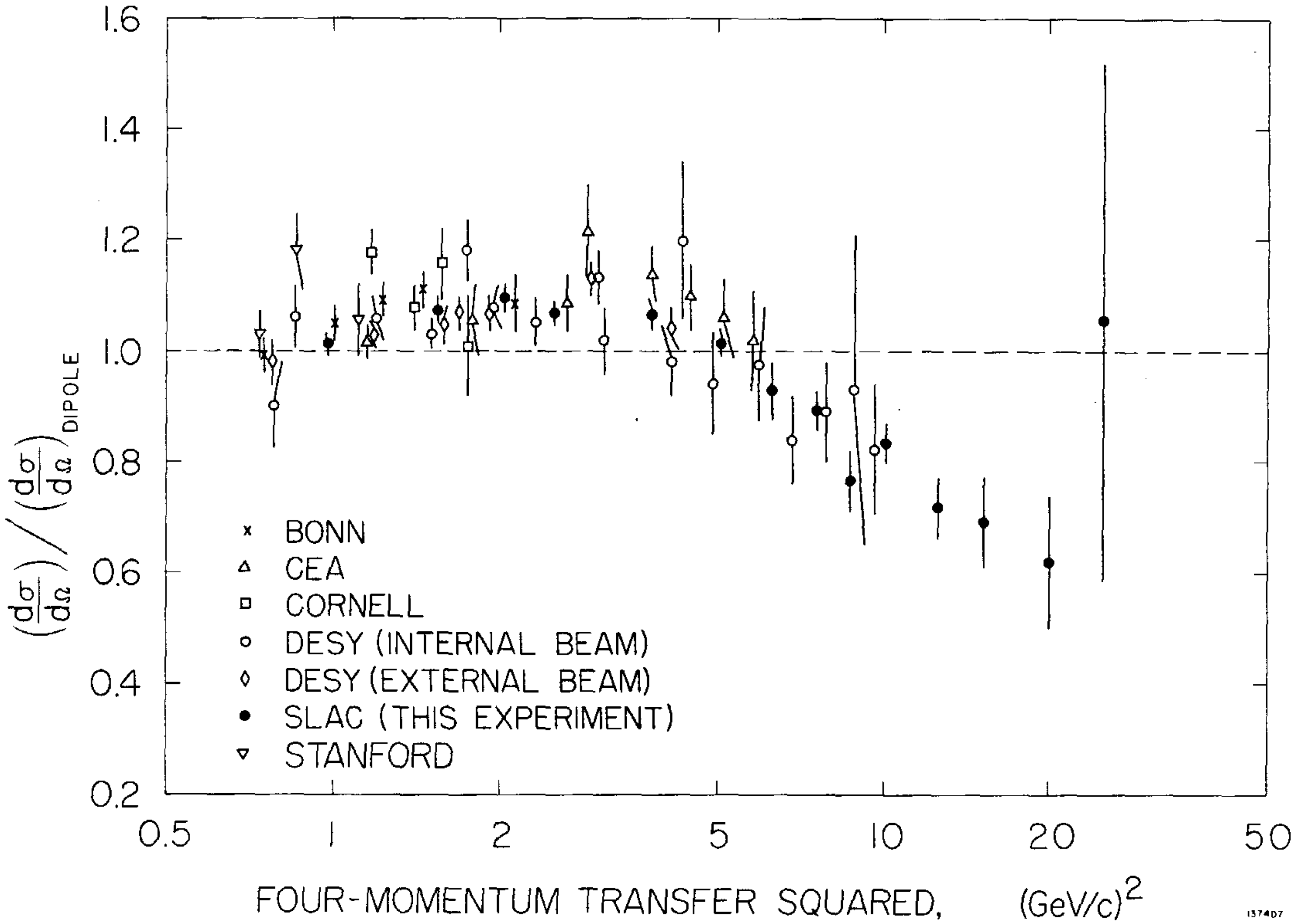
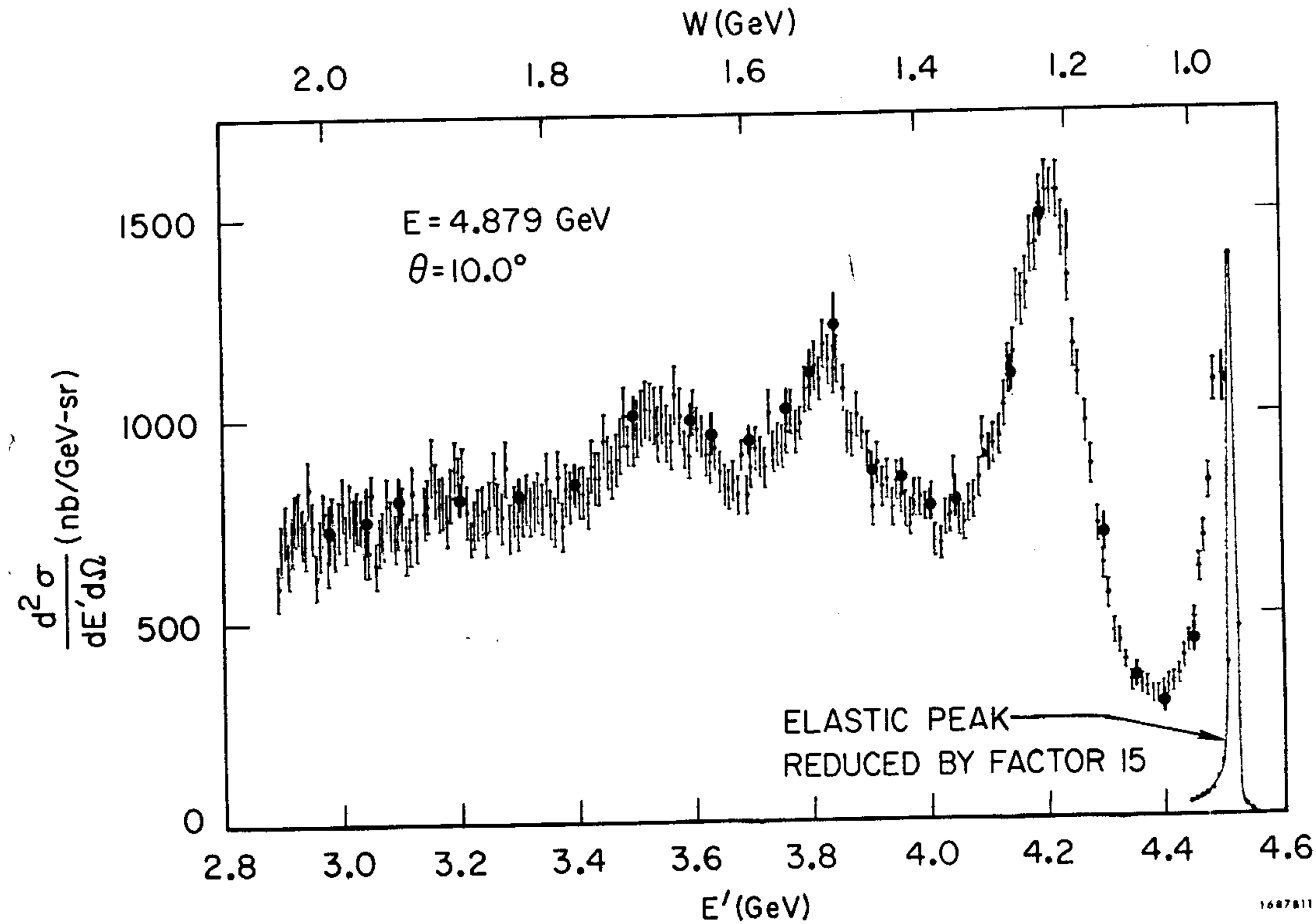
25. Dependence of measured electroweak asymmetry on polarization of the source. From C. Prescott et. al., Physics Letters 77B, 347 (1978).

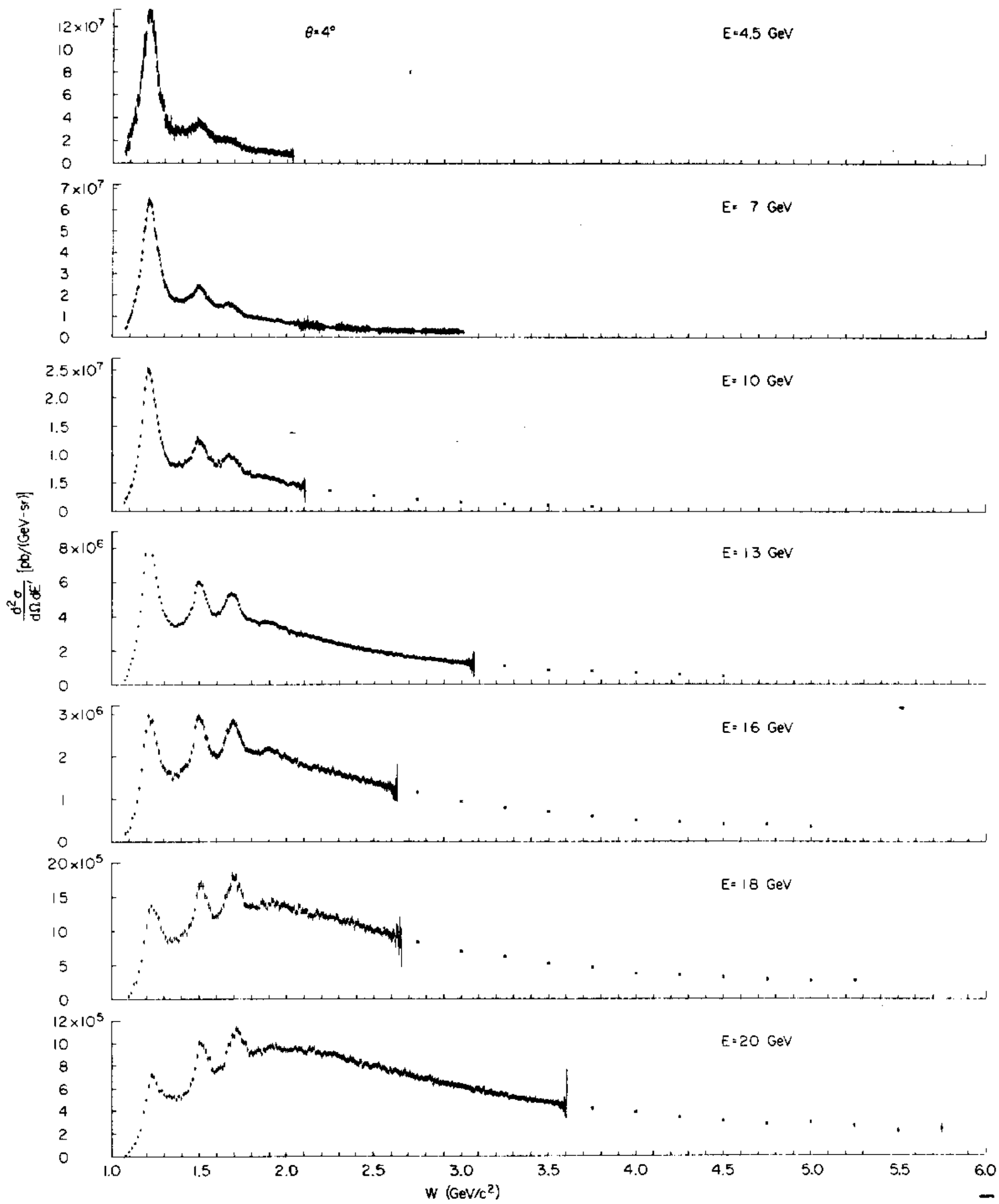
26. Dependence of measured electroweak asymmetry on electron beam energy. From C. Prescott et. al., op. cit. (Fig. 25).

27. Electroweak polarization asymmetry A/Q^2 as function of scattered electron energy, showing evidence for the "standard" model. From C. Prescott et. al., Physics Letters 84B, 524 (1979).

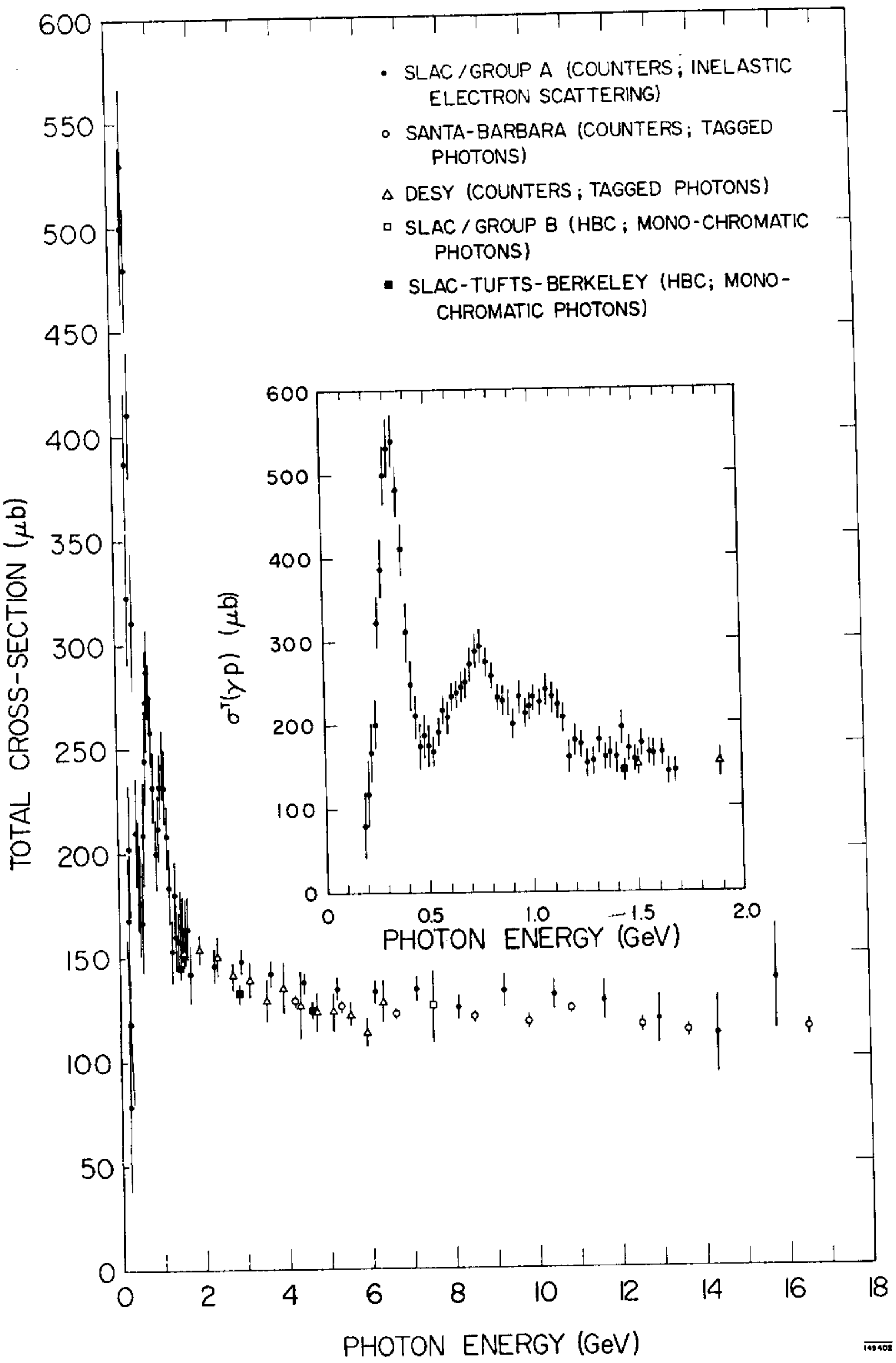

SLAC (1969)
— $G_M/\mu = (1+q^2/0.71)^{-2}$
$\frac{G_M}{\mu}$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
5
10
15
20
25
30
FOUR-MOMENTUM TRANSFER SQUARED,
q^2 (GeV/c)^2
1374C2


1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
(dσ/dΩ)/(dσ/dΩ)DIPOLE
BONN
CEA
CORNELL
DESY (INTERNAL BEAM)
DESY (EXTERNAL BEAM)
SLAC (THIS EXPERIMENT)
STANFORD
0.5
1
2
5
10
20
50
FOUR-MOMENTUM TRANSFER SQUARED, (GeV/c)2
1374D7


W (GeV)
2.0
1.8
1.6
1.4
1.2
1.0
E = 4.879 GeV
θ = 10.0°
$\frac{d^2\sigma}{dE' d\Omega}$ (nb/GeV-sr)
1500
1000
500
0
ELASTIC PEAK
REDUCED BY FACTOR 15
2.8
3.0
3.2
3.4
3.6
3.8
4.0
4.2
4.4
4.6
E′ (GeV)
1687811



θ=4°
E=4.5 GeV
E= 7 GeV
E= 10 GeV
E= 13 GeV
E= 16 GeV
E= 18 GeV
E=20 GeV
d²σ/dΩdE′ [pb/(GeV-sr)]
W (GeV/c²)
12×10⁷
7×10⁷
2.5×10⁷
8×10⁶
3×10⁶
20×10⁵
12×10⁵
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0



• SLAC / GROUP A (COUNTERS; INELASTIC ELECTRON SCATTERING)
○ SANTA-BARBARA (COUNTERS; TAGGED PHOTONS)
△ DESY (COUNTERS; TAGGED PHOTONS)
□ SLAC / GROUP B (HBC; MONO-CHROMATIC PHOTONS)
■ SLAC-TUFTS-BERKELEY (HBC; MONO-CHROMATIC PHOTONS)
TOTAL CROSS-SECTION (μb)
PHOTON ENERGY (GeV)
σT(γp) (μb)
PHOTON ENERGY (GeV)
1494D2

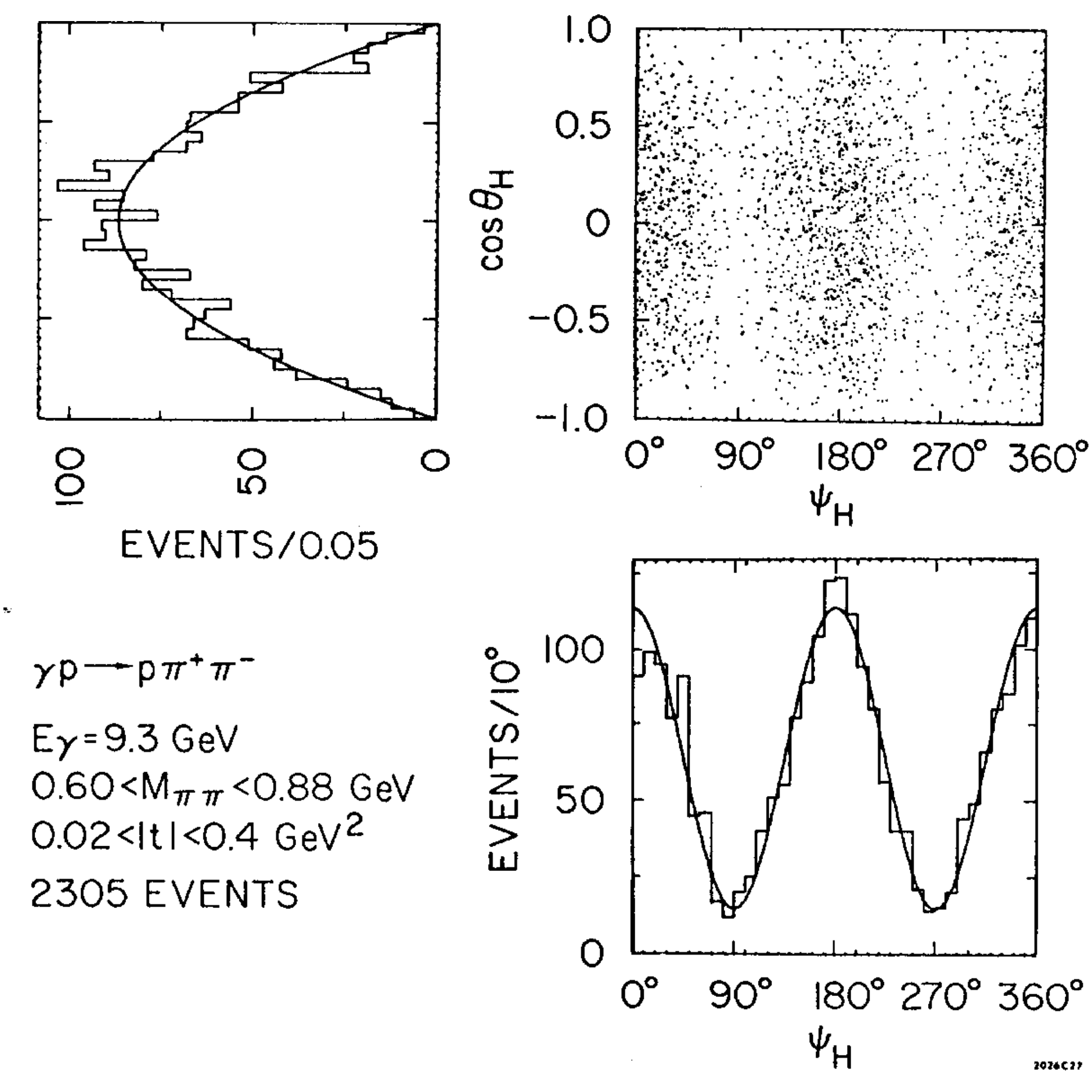

1.0
0.5
0
−0.5
−1.0
$\cos\theta_H$
0° 90° 180° 270° 360°
ψ_H
100
50
0
EVENTS/0.05
$\gamma p \rightarrow p\pi^+\pi^-$
$E\gamma = 9.3$ GeV
$0.60 < M_{\pi\pi} < 0.88$ GeV
$0.02 < |t| < 0.4$ GeV^2
2305 EVENTS
EVENTS/10°
2026C27

Fig. 7

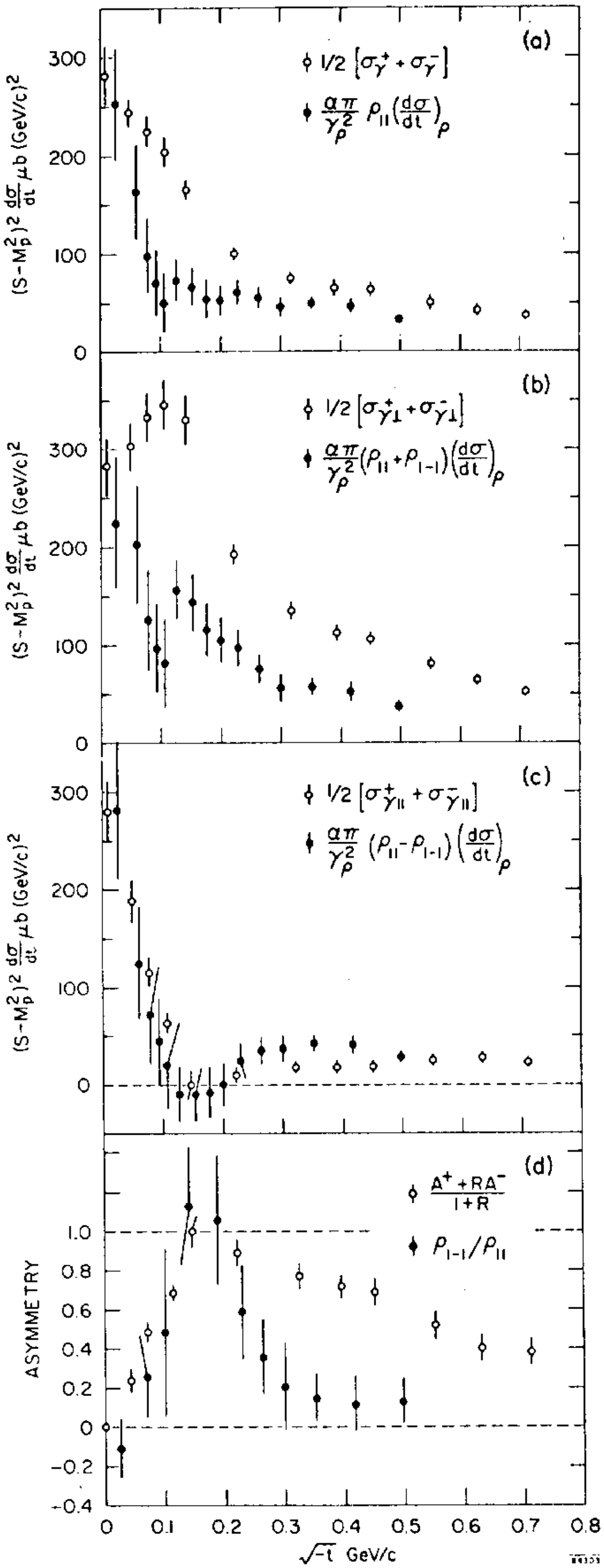
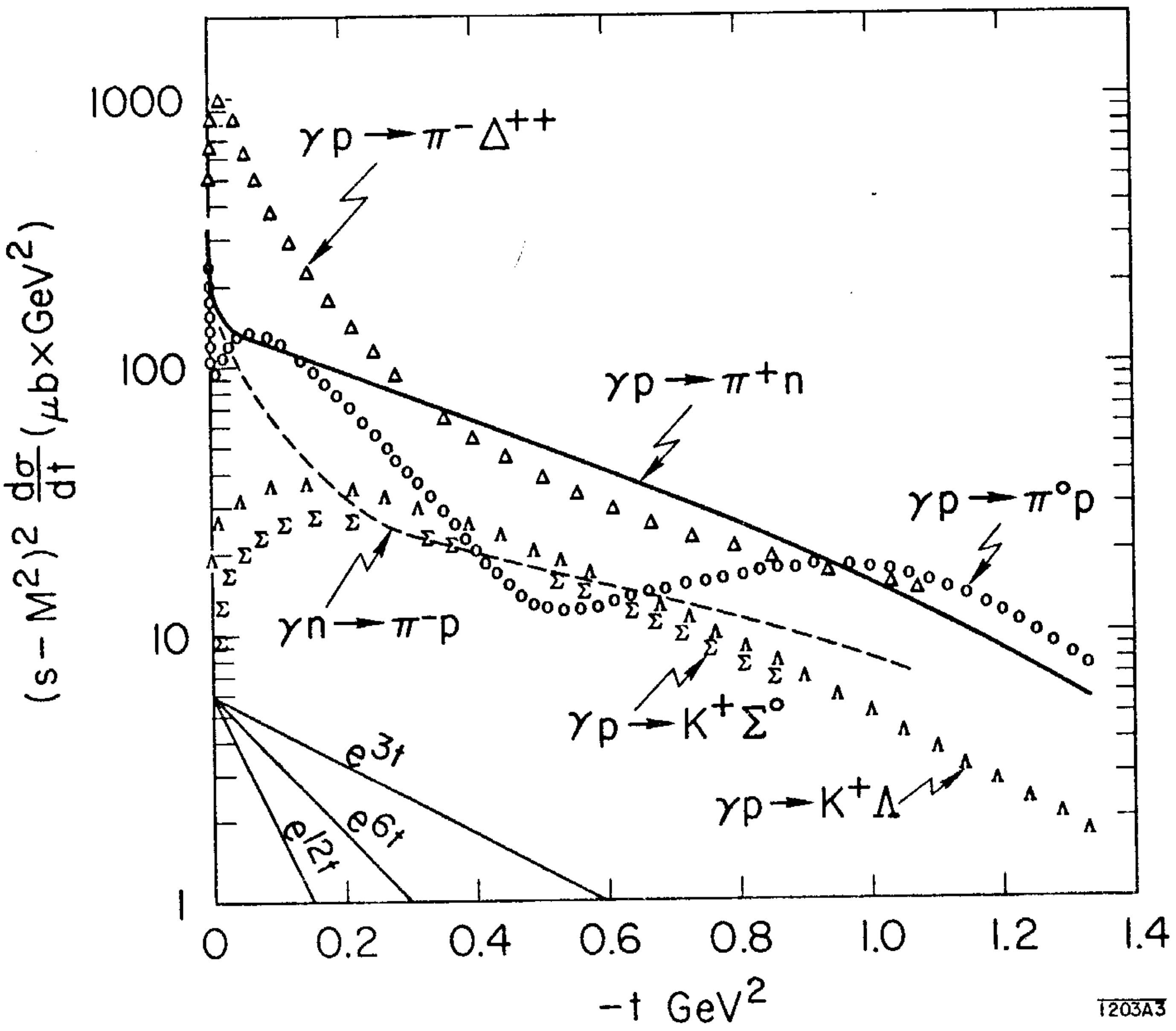

(a)
$1/2\,[\sigma_\gamma^+ + \sigma_\gamma^-]$
$\frac{\alpha\pi}{\gamma_\rho^2}\rho_{11}\left(\frac{d\sigma}{dt}\right)_\rho$
(b)
$1/2\,[\sigma_{\gamma\perp}^+ + \sigma_{\gamma\perp}^-]$
$\frac{\alpha\pi}{\gamma_\rho^2}(\rho_{11}+\rho_{1-1})\left(\frac{d\sigma}{dt}\right)_\rho$
(c)
$1/2\,[\sigma_{\gamma\parallel}^+ + \sigma_{\gamma\parallel}^-]$
$\frac{\alpha\pi}{\gamma_\rho^2}(\rho_{11}-\rho_{1-1})\left(\frac{d\sigma}{dt}\right)_\rho$
(d)
$\frac{A^+ + RA^-}{1+R}$
ρ_{1-1}/ρ_{11}
$(S-M_p^2)^2\,\frac{d\sigma}{dt}\,\mu b\,(GeV/c)^2$
ASYMMETRY
$\sqrt{-t}$ GeV/c

Fig 2



$\gamma p \rightarrow \pi^- \Delta^{++}$
$\gamma p \rightarrow \pi^+ n$
$\gamma p \rightarrow \pi^0 p$
$\gamma n \rightarrow \pi^- p$
$\gamma p \rightarrow K^+ \Sigma^0$
$\gamma p \rightarrow K^+ \Lambda$
e^{3t}
e^{6t}
e^{12t}
$(s - M^2)^2 \frac{d\sigma}{dt} (\mu b \times GeV^2)$
1000
100
10
1
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
$-t$ GeV^2
1203A3

Fig. 10

G. Smadja, R. J. Cashmore, and D.W.G.S. Leith, Report No. LBL 2637/SLAC-PUB-1390, Lawrence Berkeley Laboratory and Stanford Linear Accelerator Center, to be submitted for publication.

8. F. J. Gilman, Report No. SLAC-PUB-1320, Stanford Linear Accelerator Center. Lectures presented at 14th Scottish Universities in Physics, August, 1973. J. Rosner, Review talk given at Berkeley APS Meeting on High Energy Physics, 1973; p. 130. D. Faiman, Weizmann Institute preprint WIS 74/16.

9. R. J. Cashmore, D.W.G.S. Leith, R. S. Longacre, and A. H. Rosenfeld, Report No. LBL 2635/SLAC-PUB-1388, Lawrence Berkeley Laboratory and Stanford Linear Accelerator Center, to be submitted for publication.

10. R. J. Cashmore, D.W.G.S. Leith, R. S. Longacre, A. H. Rosenfeld, G. P. Gopal, R. A. Stevens, V. Tayler, and A. White, Report No. LBL 2634/SLAC-PUB-1387, Lawrence Berkeley Laboratory and Stanford Linear Accelerator Center, to be submitted for publication.

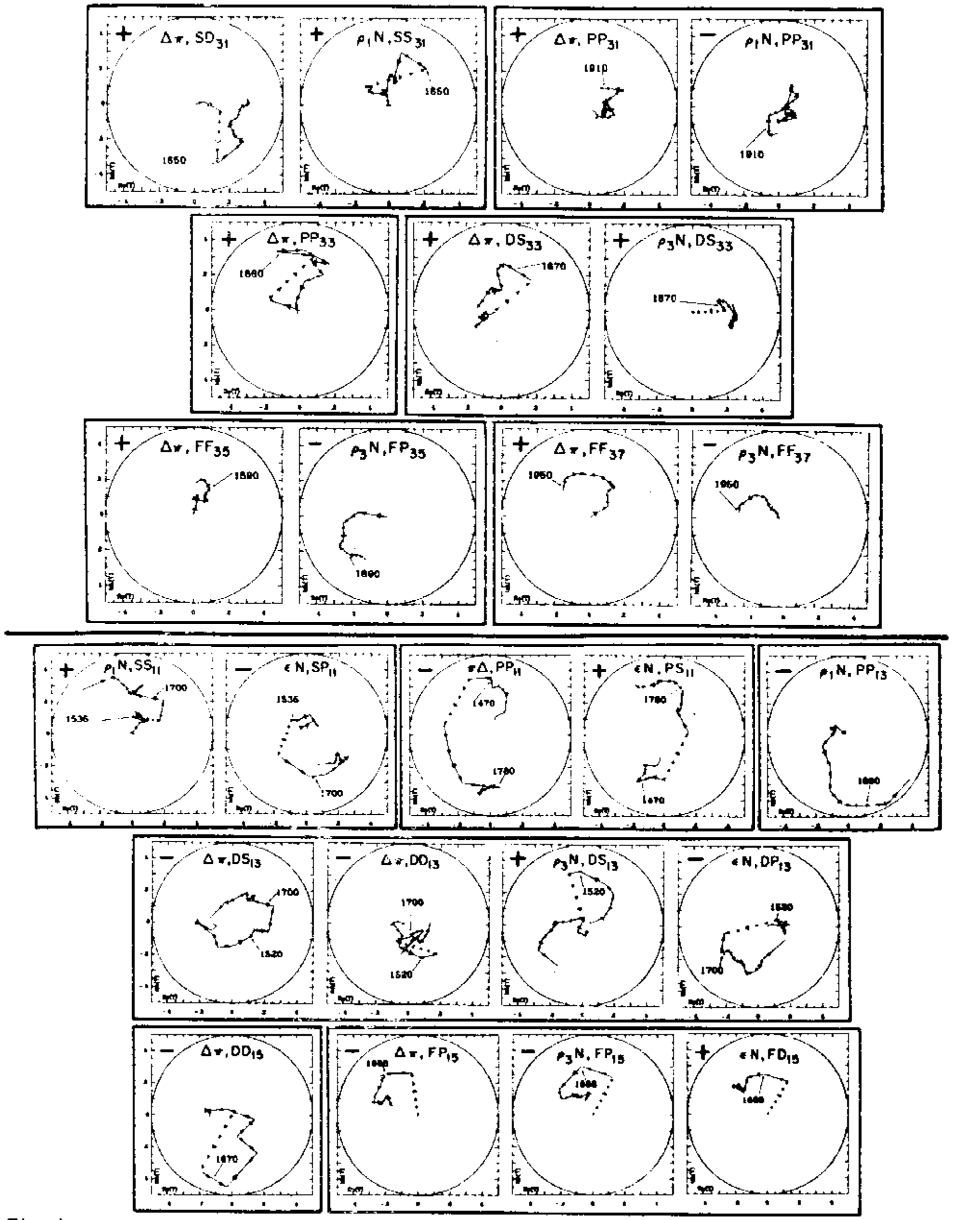


Fig. 1. Argand plots for Solutuion A (1972). The nominal energies come from the CERN 1972 partial wave analysis. For more details, see combined caption for both figures, at the end of the text.

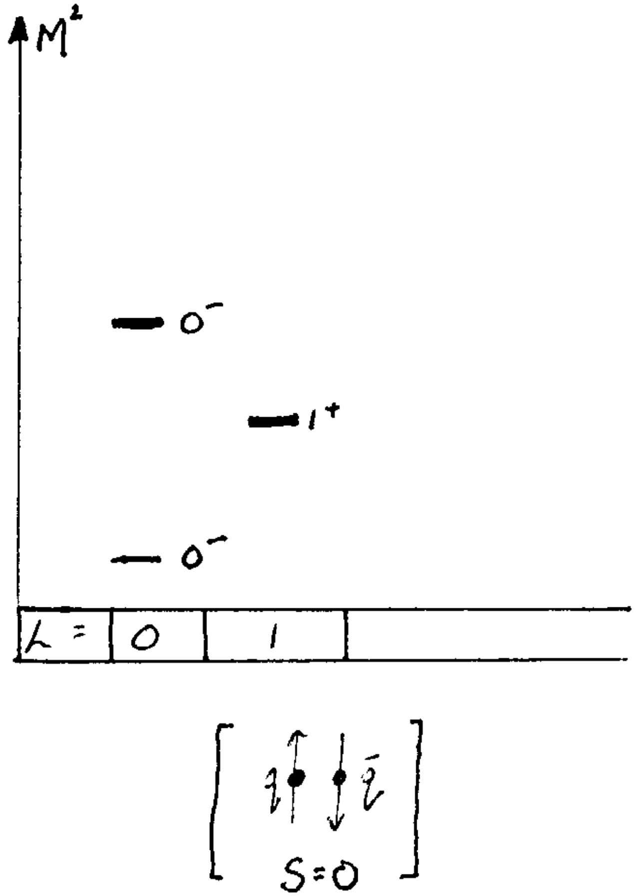
XBL 745-778

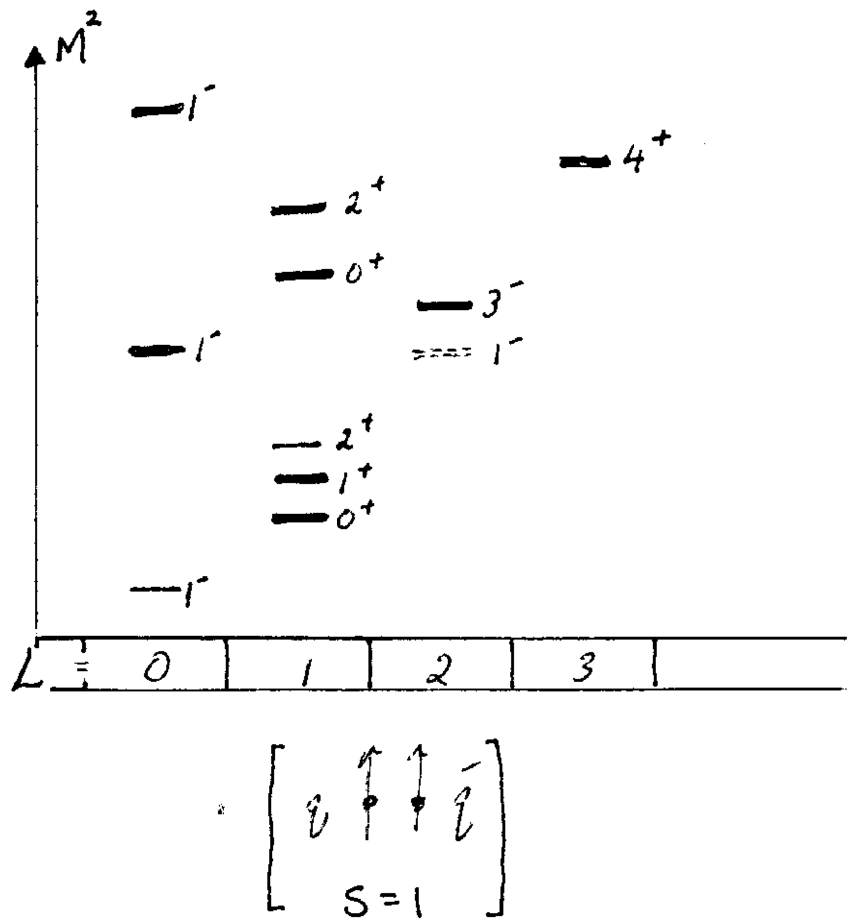
7-21-82 K.

K^* STATES:

~~Heavy~~ Light ~~Red Line~~ Line - WELL UNDERSTOOD BY OTHERS.

Heavy ~~Blue~~ Line - STATES DISCOVERED / BY SLAC GROUP. / AND/OR STUDIED





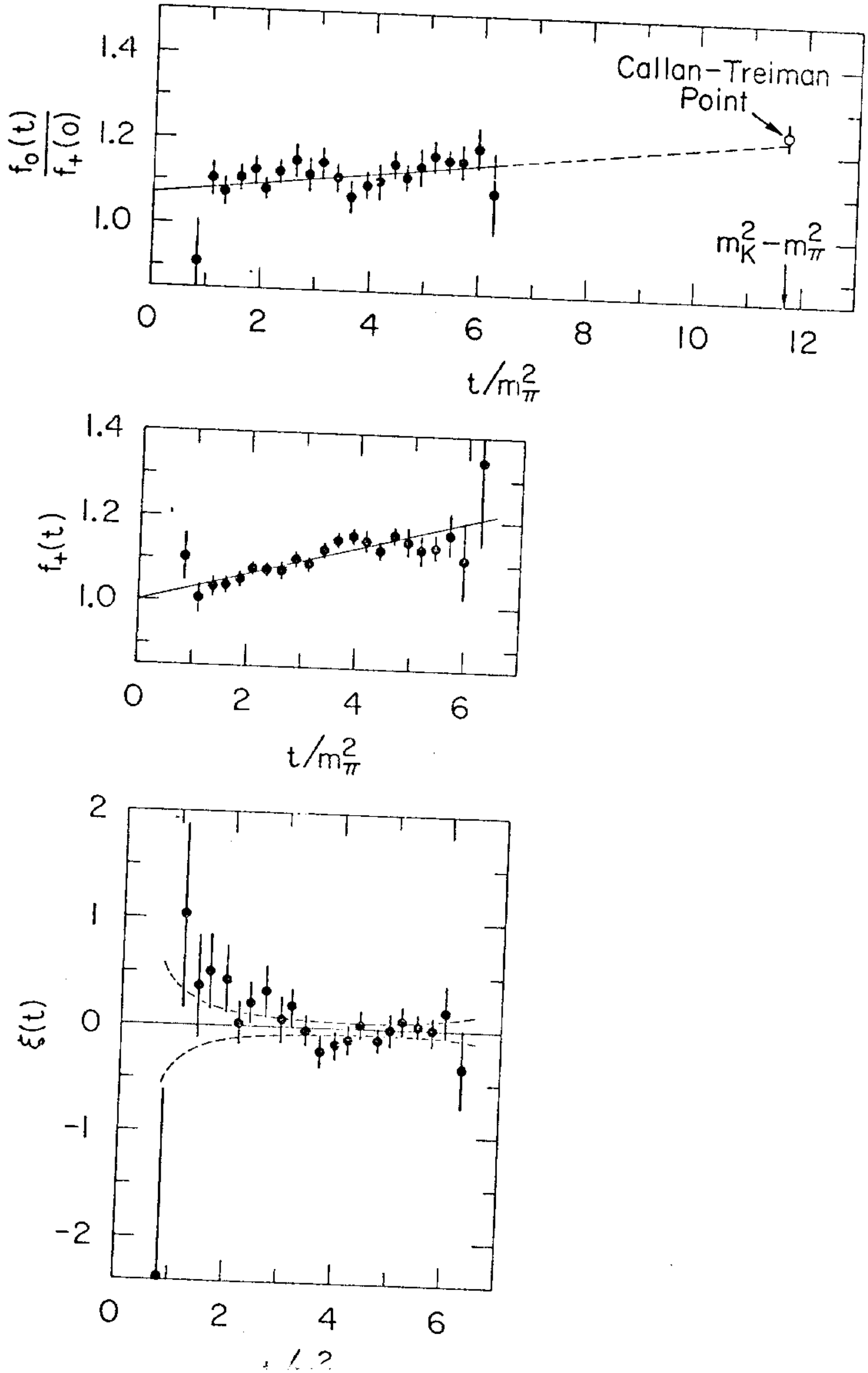

1.4
1.2
1.0
$\frac{f_0(t)}{f_+(0)}$
Callan-Treiman Point
$m_K^2 - m_\pi^2$
0
2
4
6
8
10
12
t/m_π^2
1.4
1.2
1.0
$f_+(t)$
0
2
4
6
t/m_π^2
2
1
0
-1
-2
$\xi(t)$
0
2
4
6

Fig. 15

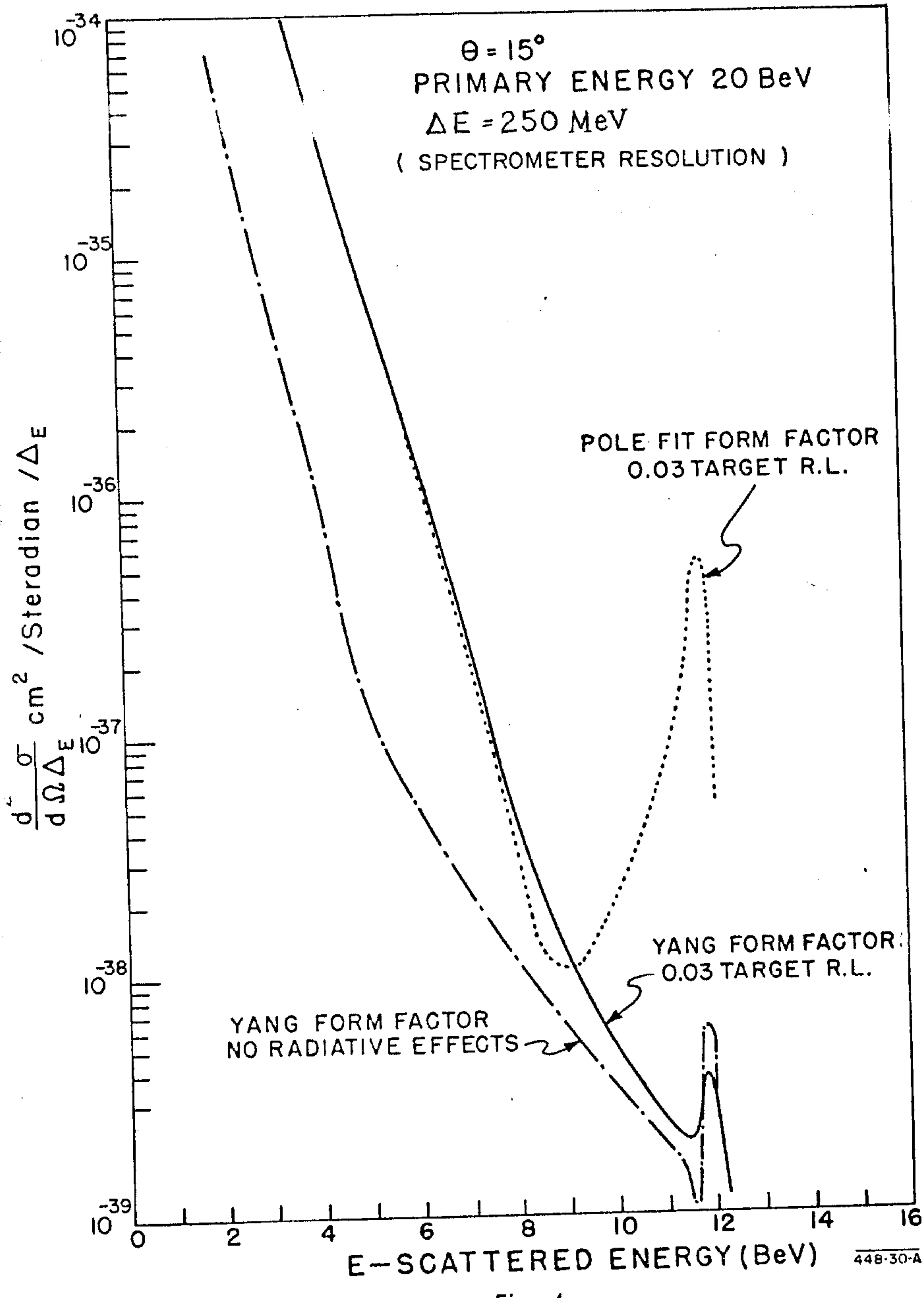
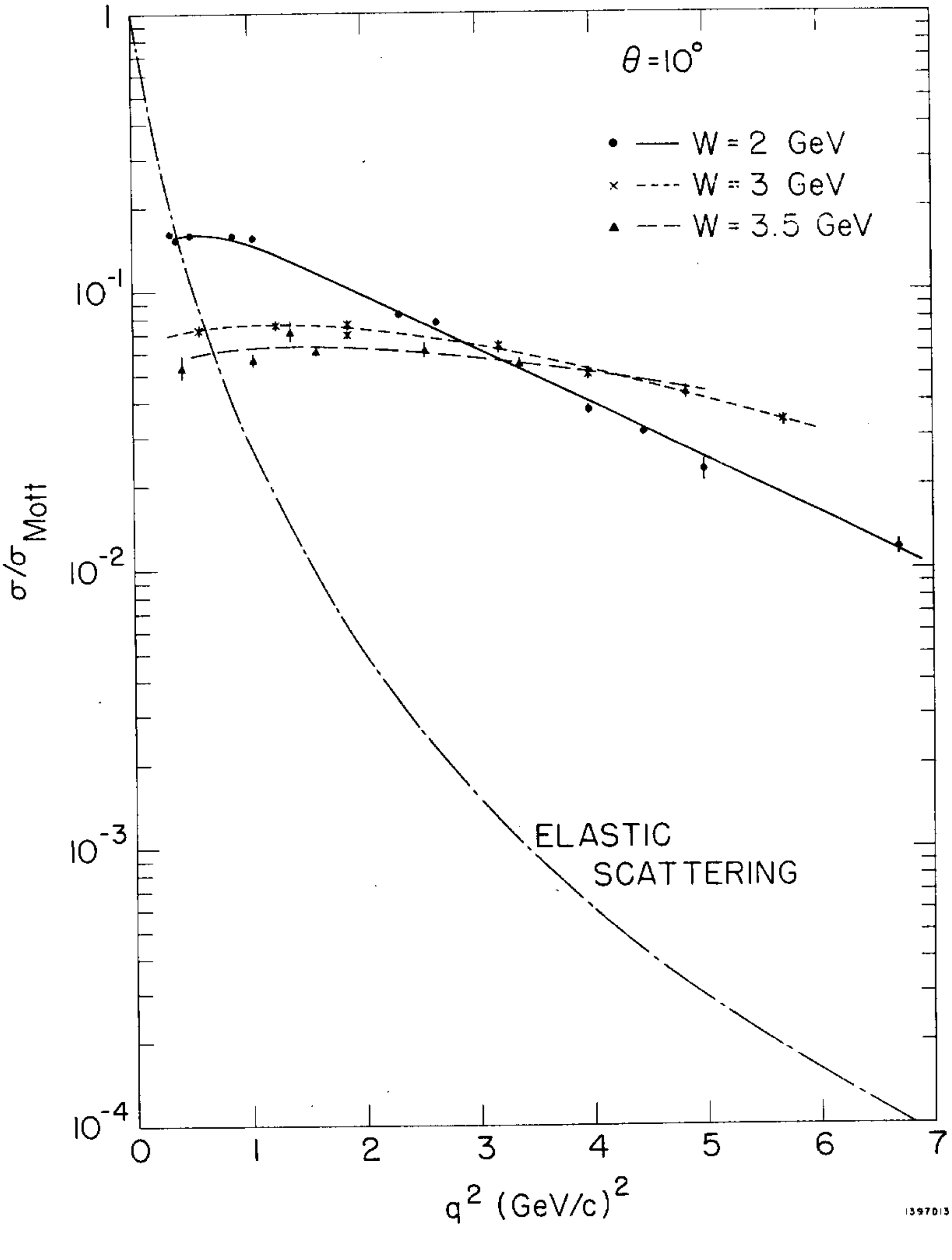
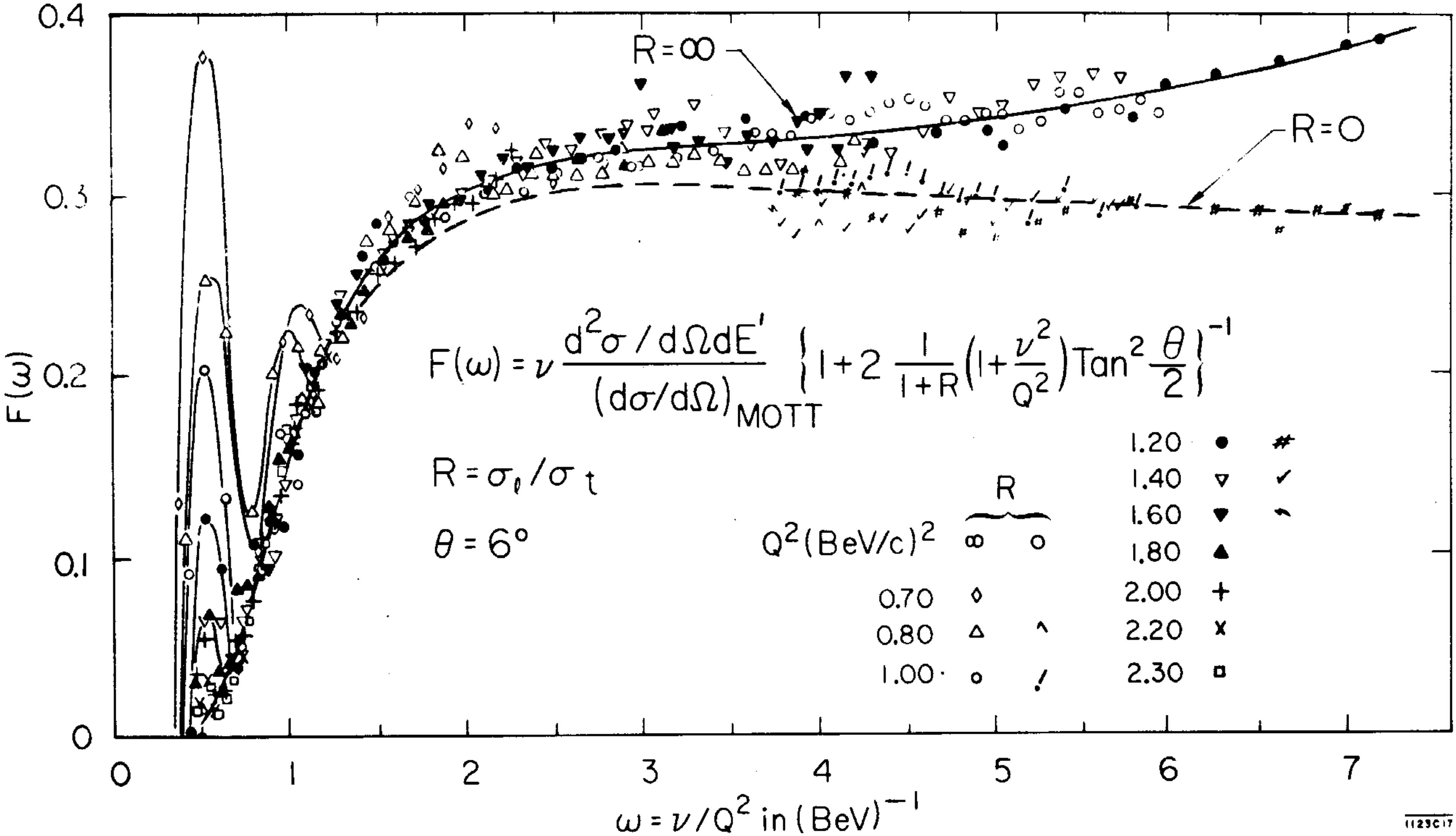

θ = 15°
PRIMARY ENERGY 20 BeV
ΔE = 250 MeV
(SPECTROMETER RESOLUTION)
POLE FIT FORM FACTOR
0.03 TARGET R.L.
YANG FORM FACTOR
0.03 TARGET R.L.
YANG FORM FACTOR
NO RADIATIVE EFFECTS
$\frac{d^2\sigma}{d\Omega\Delta_E}$ cm^2 /Steradian /Δ_E
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
0
2
4
6
8
10
12
14
16
E—SCATTERED ENERGY (BeV)
448-30-A

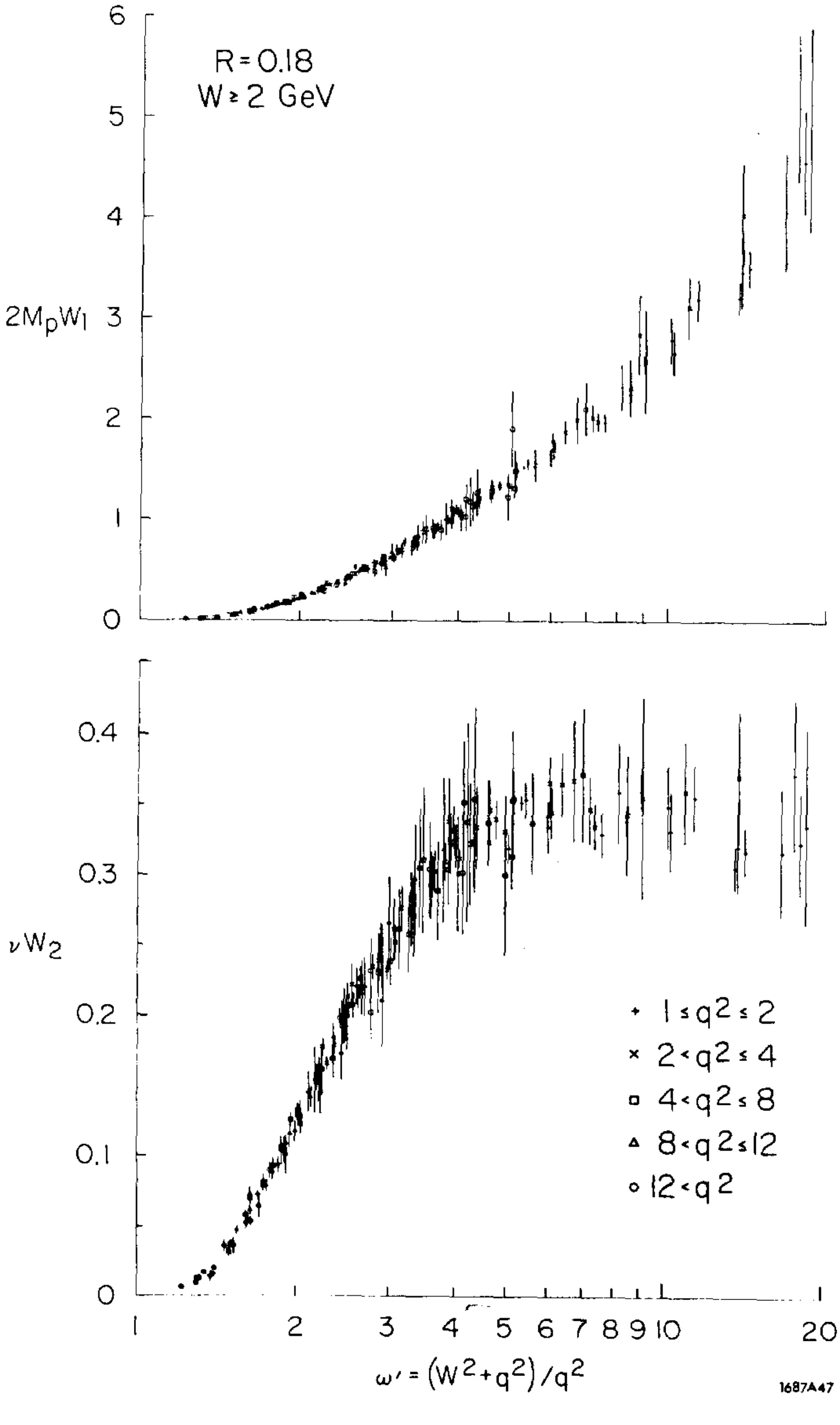
Fig. 4

Cross section much larger than elastic





R = ∞
R = 0
F(ω)
0.4
0.3
0.2
0.1
0
$F(\omega) = \nu \frac{d^2\sigma / d\Omega dE'}{(d\sigma/d\Omega)_{MOTT}} \left\{ 1 + 2 \frac{1}{1+R} \left(1 + \frac{\nu^2}{Q^2} \right) \mathrm{Tan}^2 \frac{\theta}{2} \right\}^{-1}$
$R = \sigma_l / \sigma_t$
$\theta = 6°$
R
$Q^2 (BeV/c)^2$ ∞ 0
0.70 ◇
0.80 △ ^
1.00 ○ !
1.20 ● #
1.40 ▽ ✓
1.60 ▼
1.80 ▲
2.00 +
2.20 x
2.30 □
0 1 2 3 4 5 6 7
$\omega = \nu / Q^2$ in $(BeV)^{-1}$
1123C17



R = 0.18
W ≥ 2 GeV
2MpW1
6
5
4
3
2
1
0
νW2
0.4
0.3
0.2
0.1
0
+ 1 ≤ q2 ≤ 2
× 2 < q2 ≤ 4
□ 4 < q2 ≤ 8
△ 8 < q2 ≤ 12
○ 12 < q2
1
2
3
4
5
6
7
8
9
10
20
ω' = (W2 + q2)/q2
1687A47

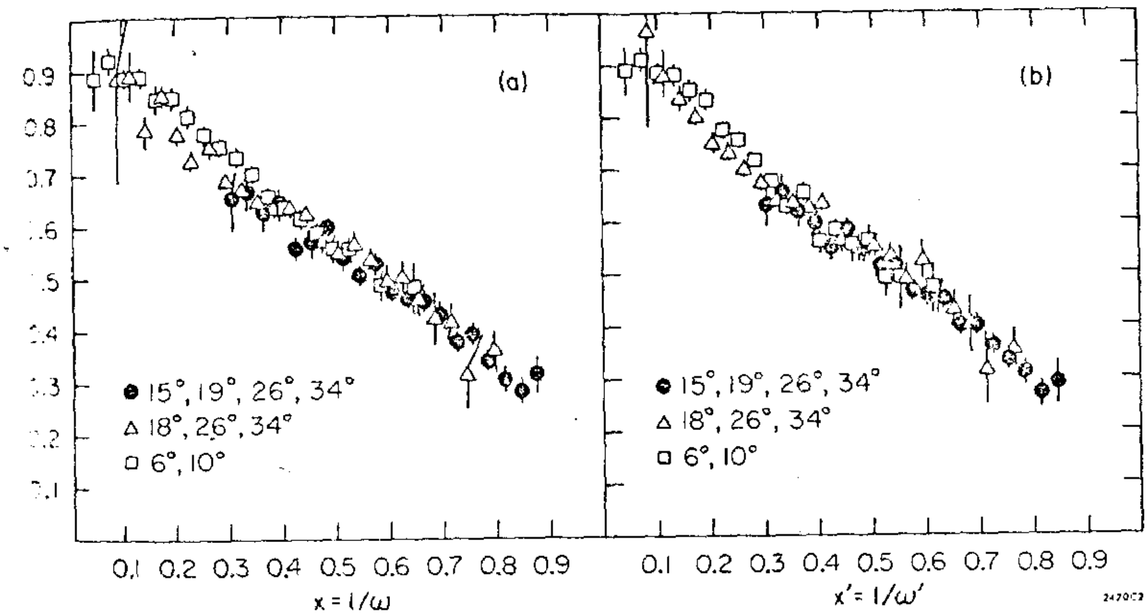
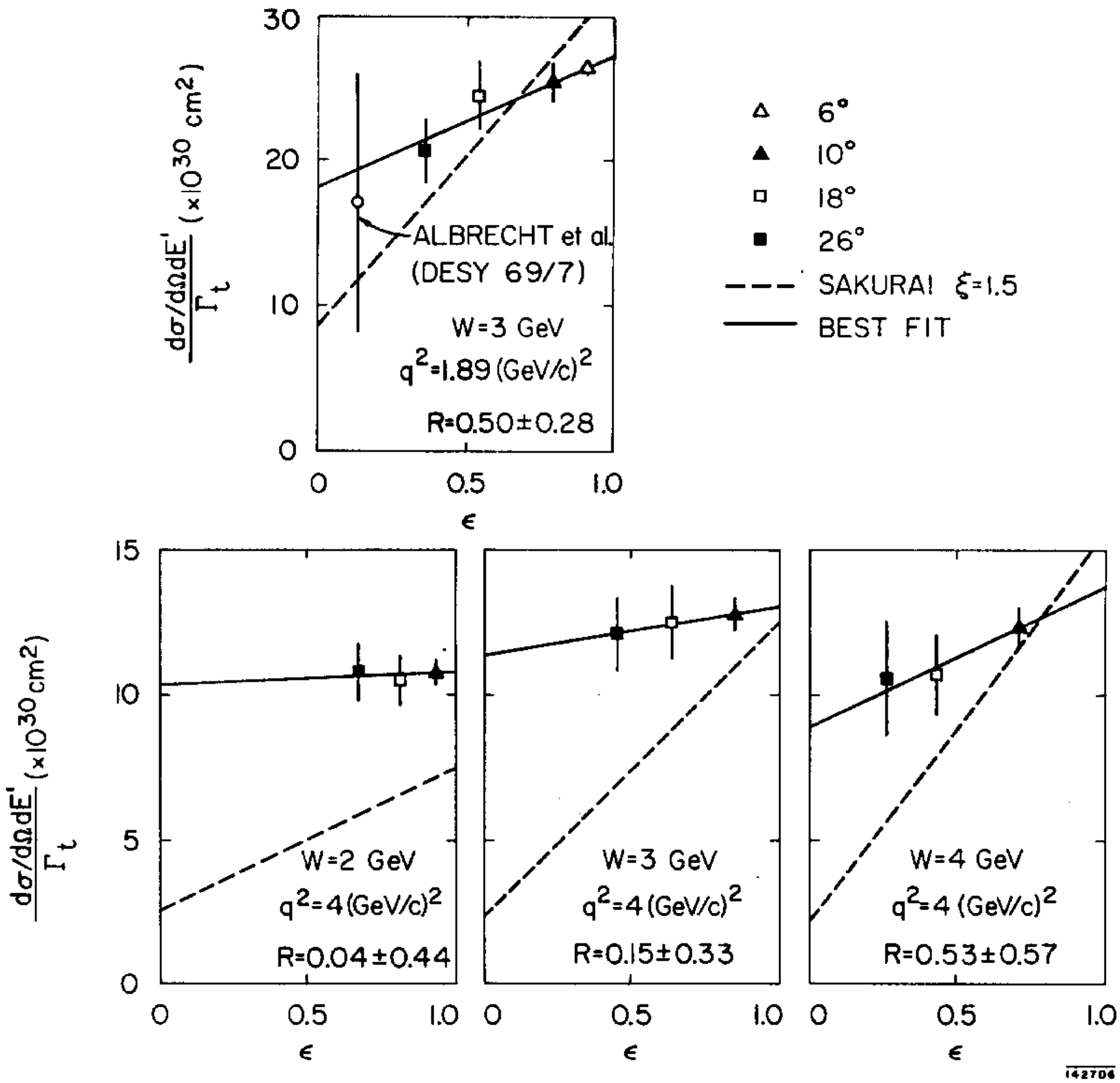
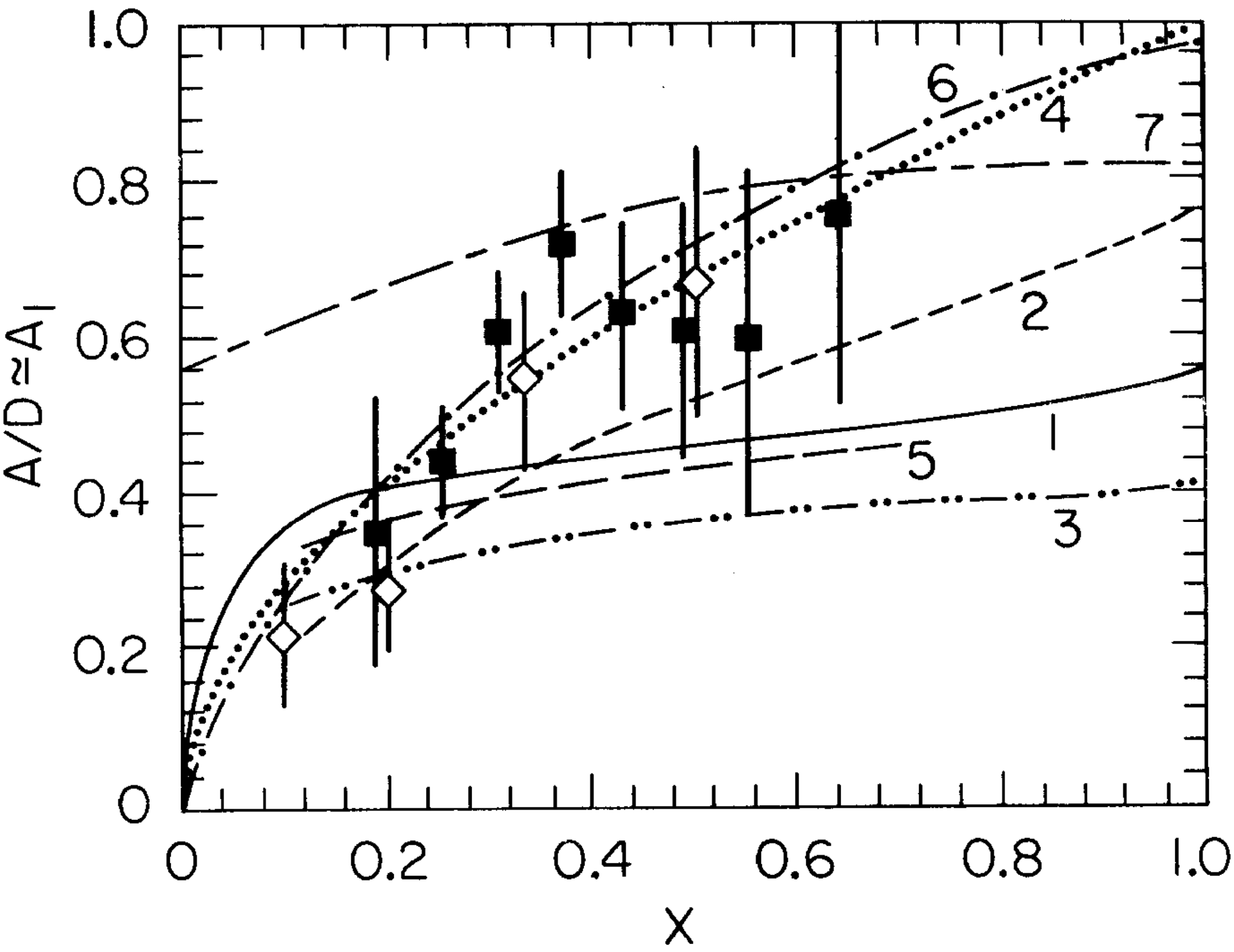


Fig. 25(a),(b). Values of σ_n/σ_p as determined from experiments A, B, and C as functions of x and x′ respectively.

Separation of structure functions

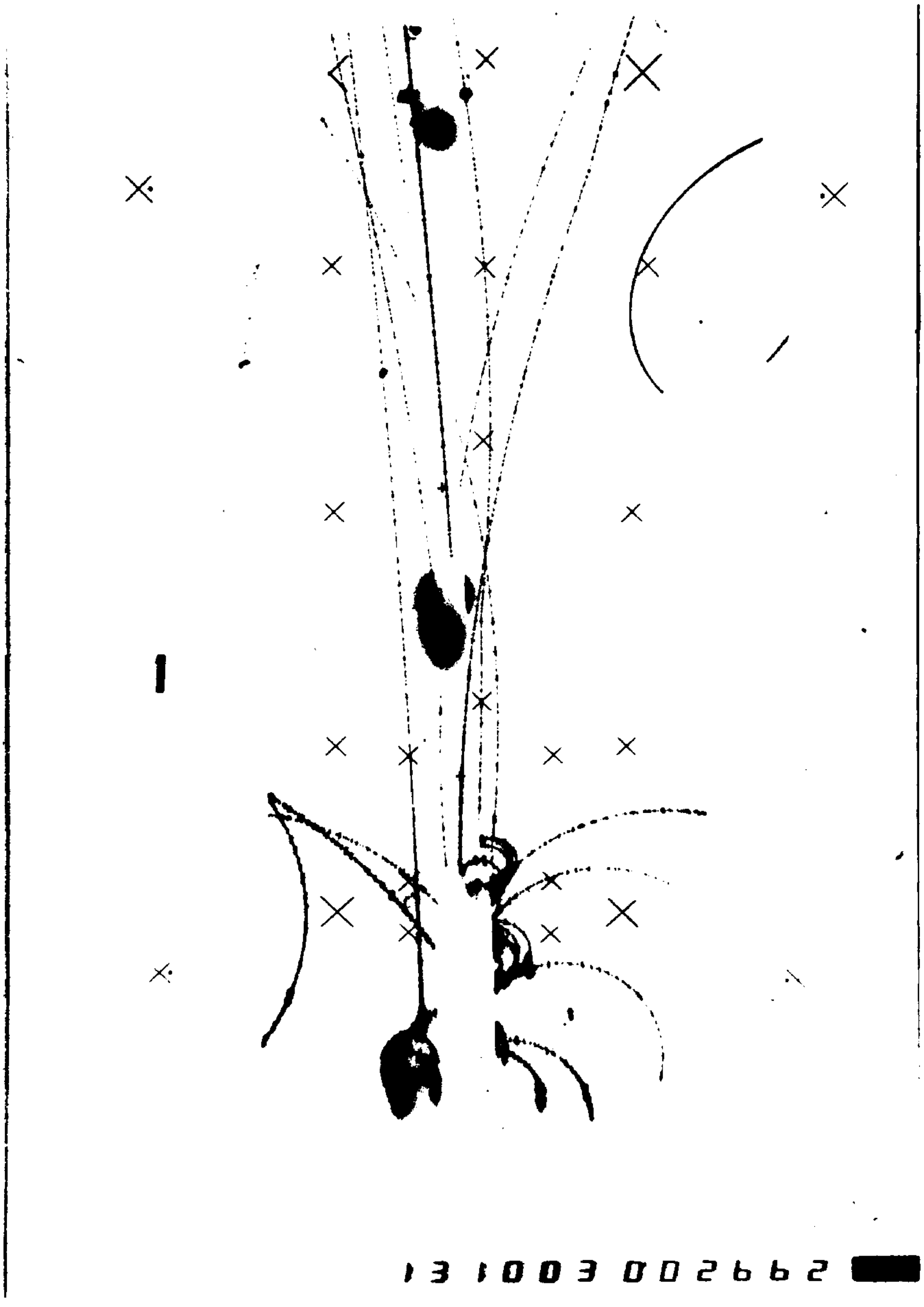
SEPARATION OF σ_S AND σ_T USING PRELIMINARY 18° & 26° DATA





1. Symmetrical Valence Quark Model (Kuti, Weisskopf, 1971).
2. Current Quarks (Close, 1974).
3. Orbital Angular Momentum, (Look, Fischbach, Sehgal, 1977).
4. Unsymmetrical Model (Carlitz, Kaur, 1977).
5. MIT Bag Model (Jaffe, Hughes, 1977).
6. Source Theory (Schwinger, 1977).
7. Quark-Geometrodynamics (Preparata, 1981).

7-82 4301B2


1
13 1003 002662

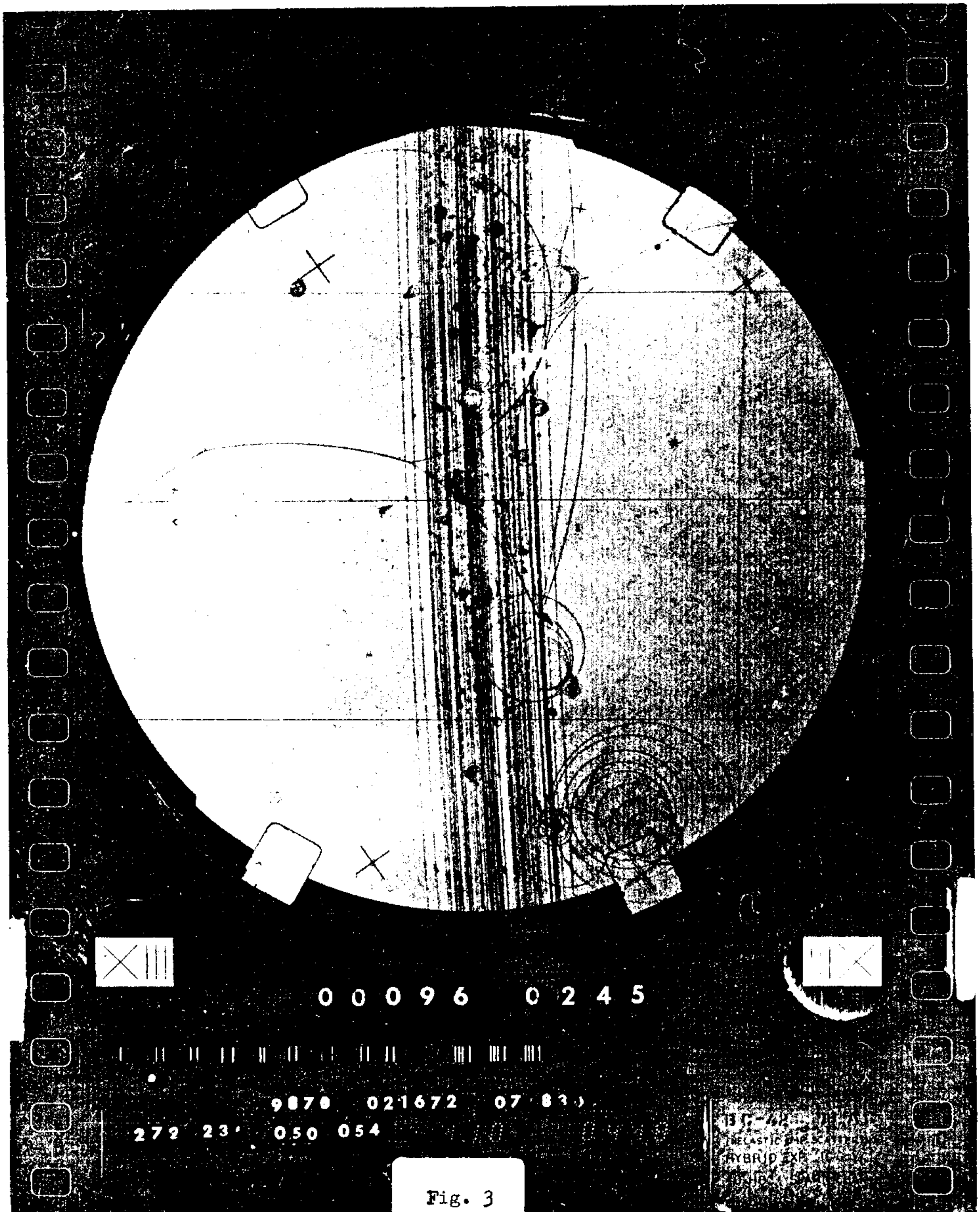


Fig. 3

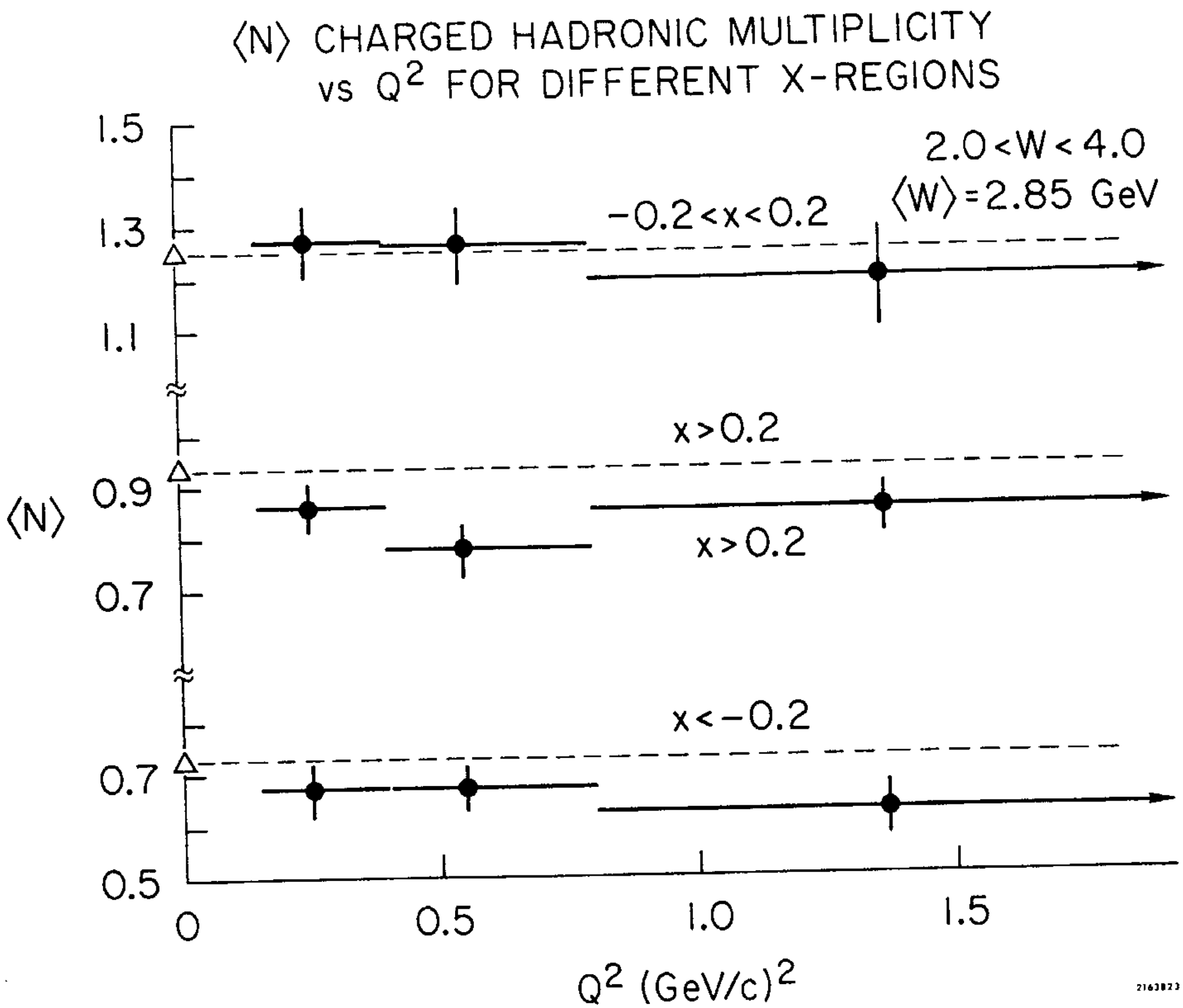
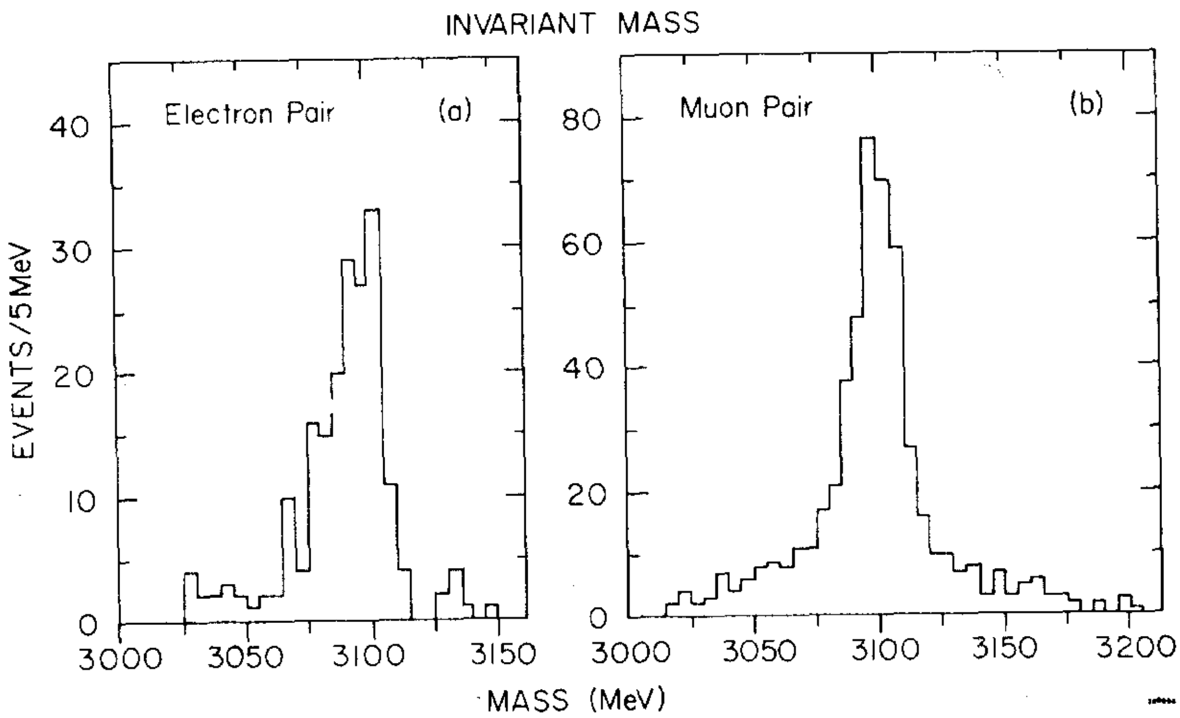

⟨N⟩ CHARGED HADRONIC MULTIPLICITY
vs Q² FOR DIFFERENT X-REGIONS
2.0 < W < 4.0
⟨W⟩ = 2.85 GeV
−0.2 < x < 0.2
x > 0.2
x > 0.2
x < −0.2
⟨N⟩
1.5
1.3
1.1
0.9
0.7
0.7
0.5
0
0.5
1.0
1.5
Q² (GeV/c)²
2163823

Fig. 6b


INVARIANT MASS
Electron Pair
(a)
Muon Pair
(b)
EVENTS/5MeV
0
10
20
30
40
0
20
40
60
80
3000
3050
3100
3150
3000
3050
3100
3150
3200
MASS (MeV)

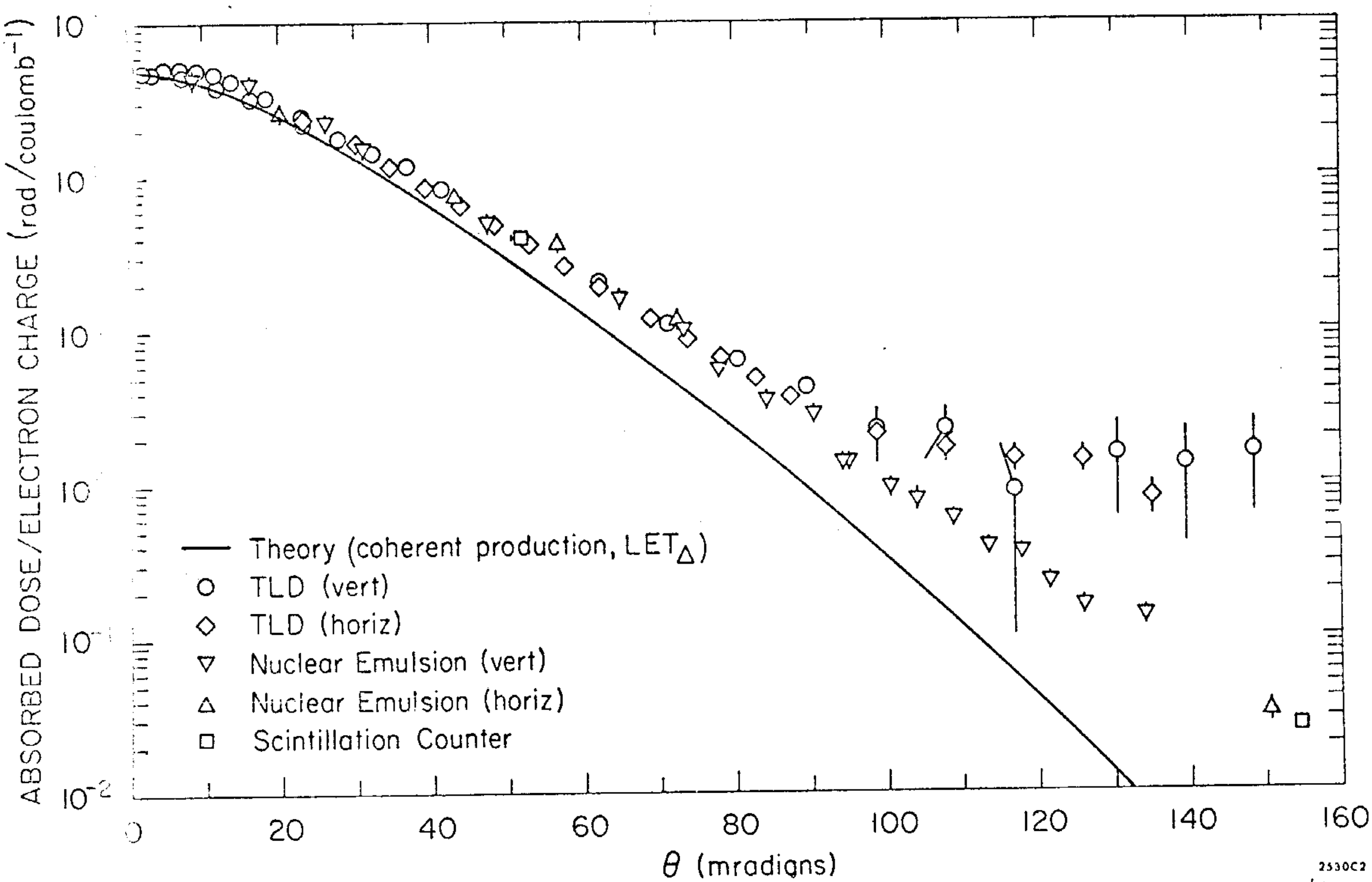
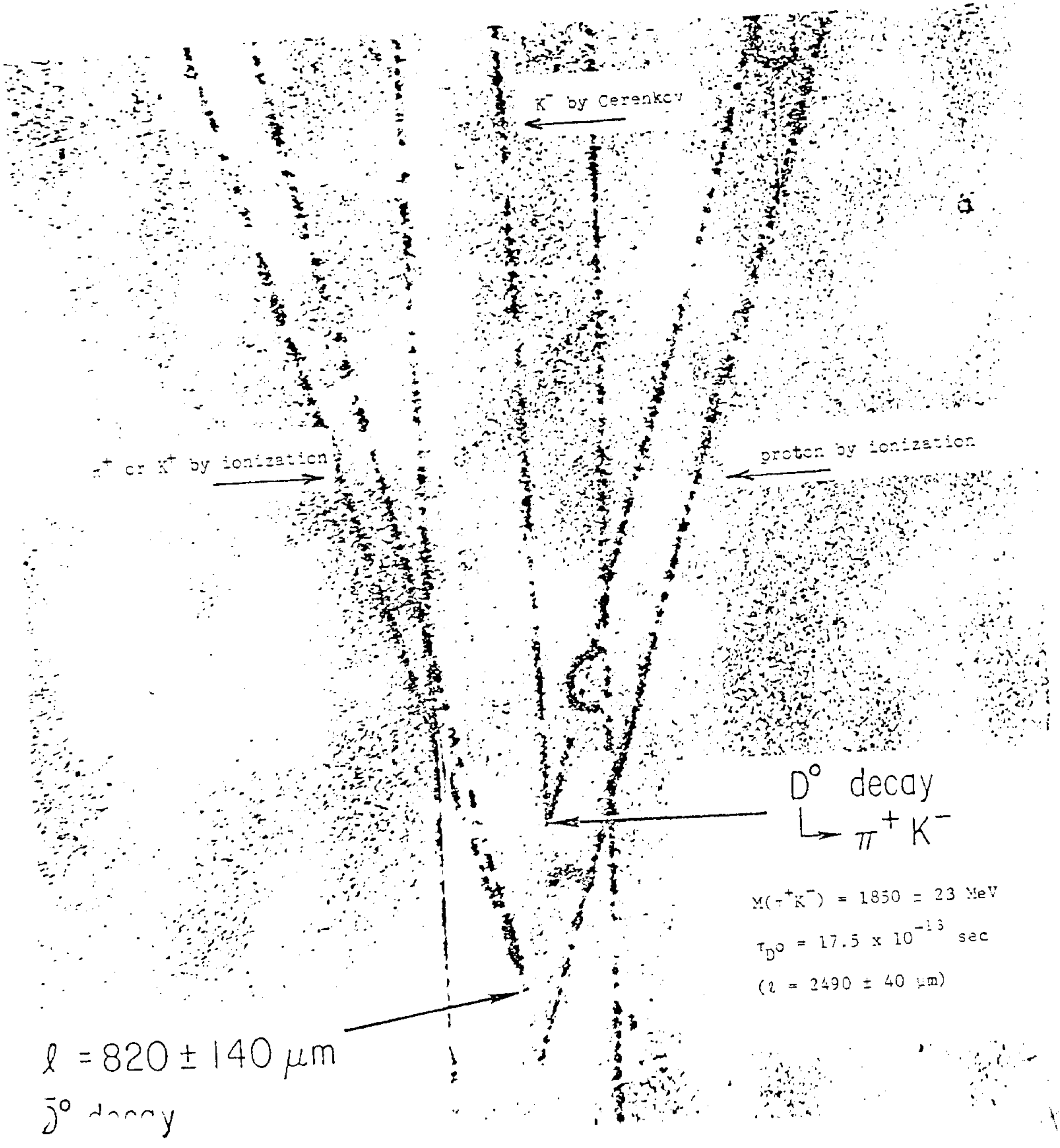
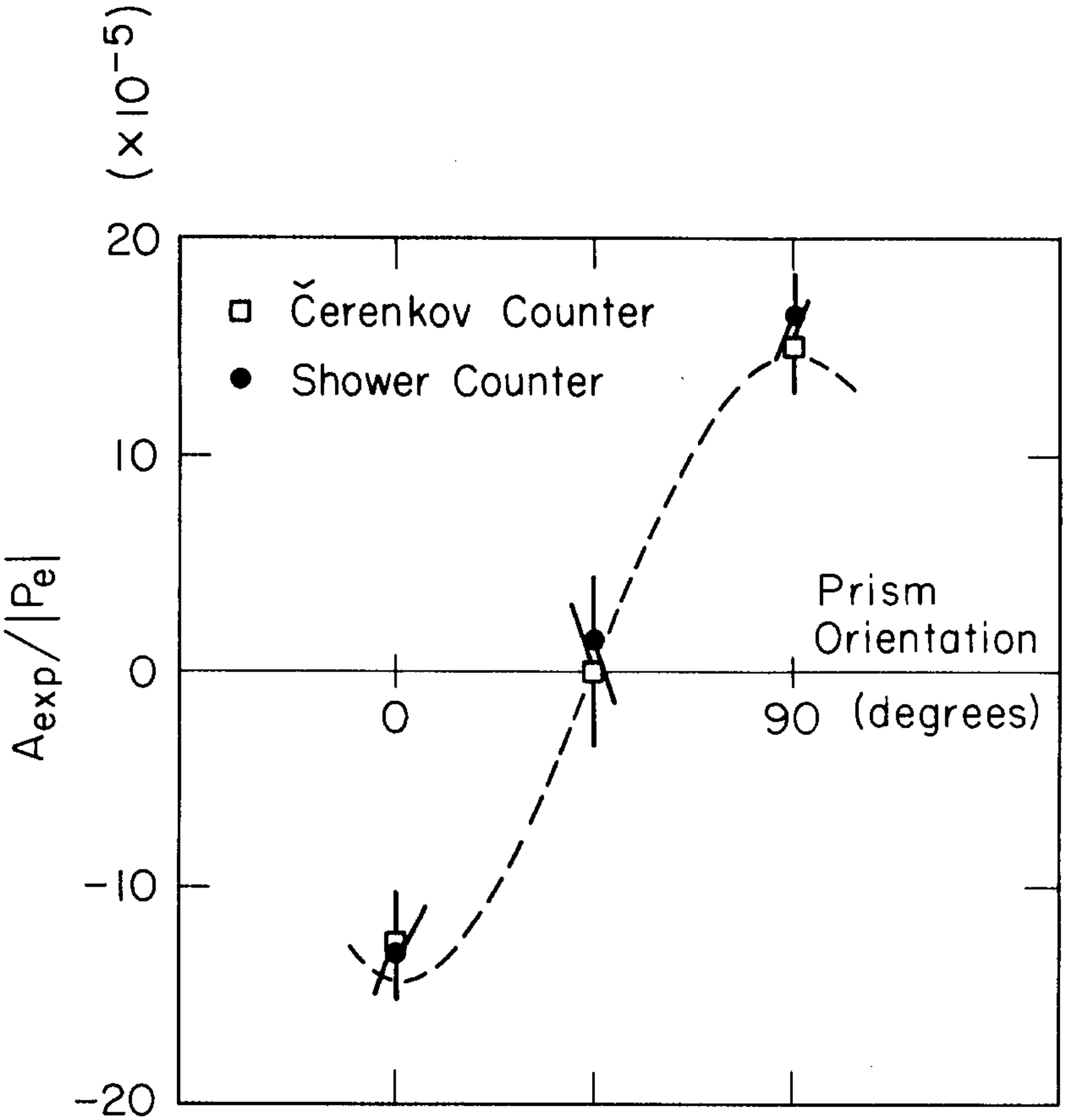

ABSORBED DOSE/ELECTRON CHARGE (rad/coulomb^{-1})
10
10
10
10
10^{-1}
10^{-2}
Theory (coherent production, LET_{Δ})
TLD (vert)
TLD (horiz)
Nuclear Emulsion (vert)
Nuclear Emulsion (horiz)
Scintillation Counter
0
20
40
60
80
100
120
140
160
θ (mradians)
2530C2

Figure 1b: An event with two neutral charmed particle decays. The first contains missing neutrals and the second is consistent with a fully reconstructed D^o decay.

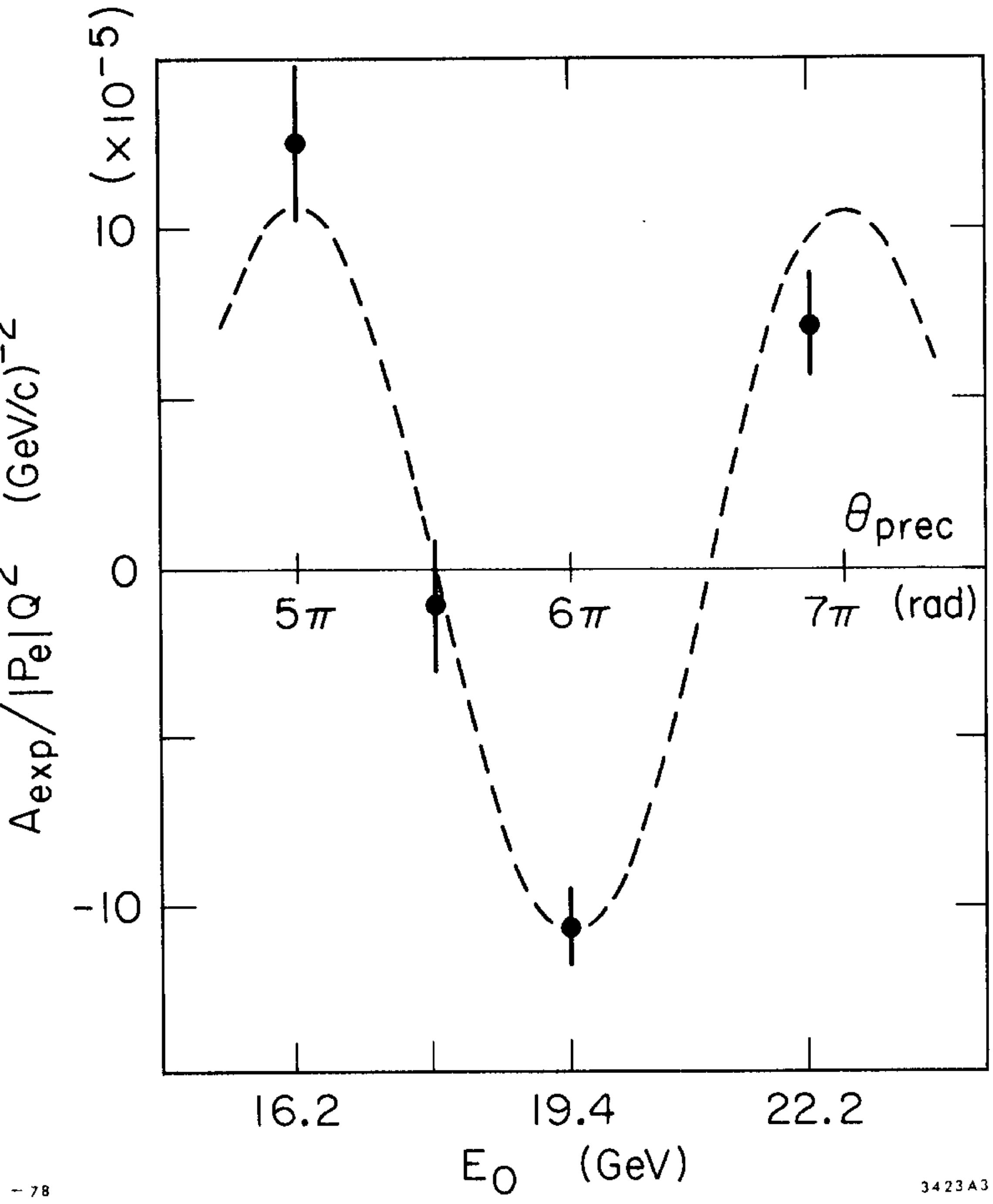




(×10⁻⁵)
$A_{exp}/|P_e|$
20
10
0
-10
-20
Čerenkov Counter
Shower Counter
Prism
Orientation
0
90
(degrees)

6 - 78

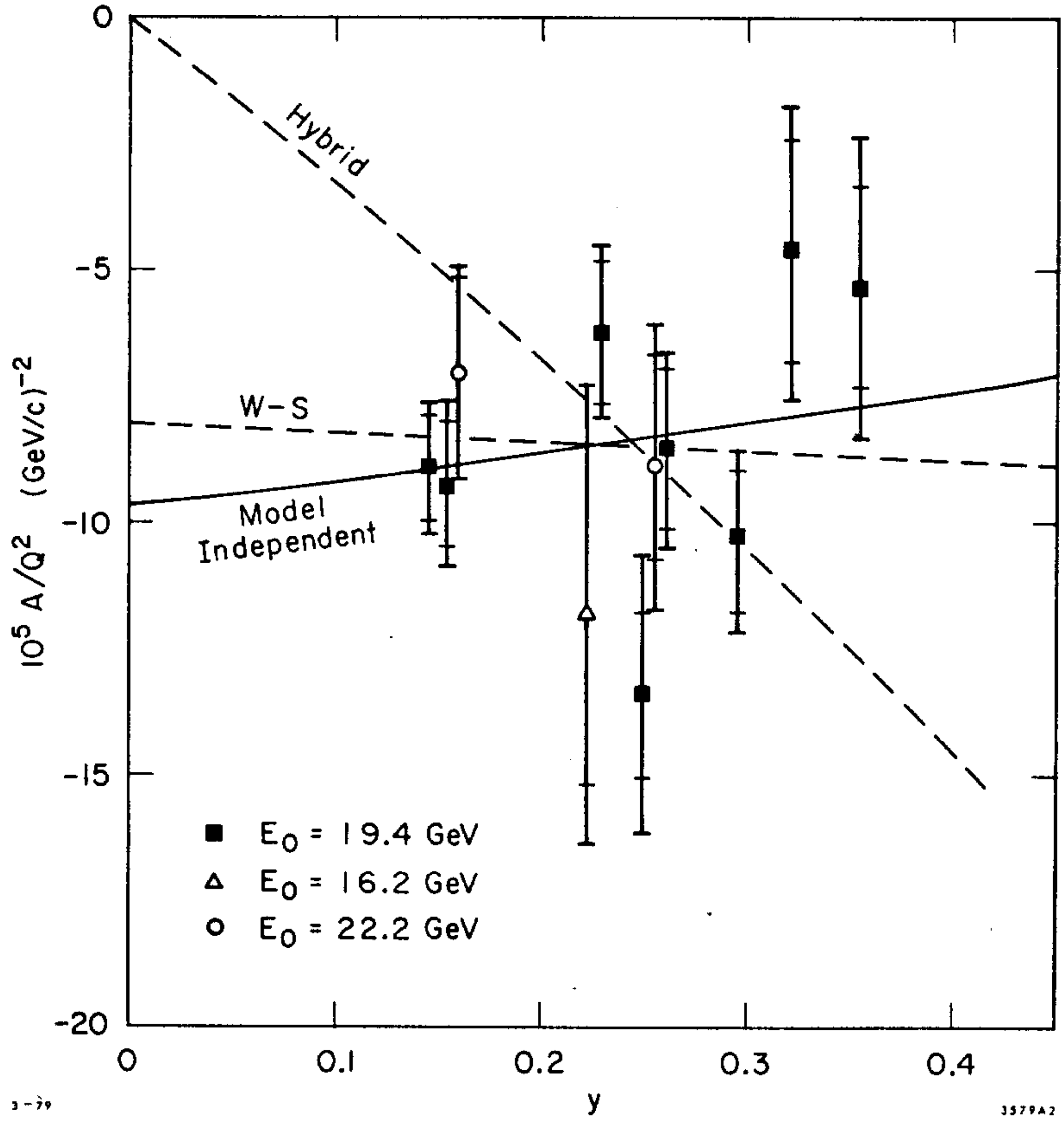
3423A2



$A_{exp}/|P_e|Q^2$ $(GeV/c)^{-2}$ $(\times 10^{-5})$
10
0
-10
θ_{prec}
5π
6π
7π
(rad)
16.2
19.4
22.2
E_0 (GeV)

6 - 78

3423A3



Hybrid
W-S
Model Independent
E_0 = 19.4 GeV
E_0 = 16.2 GeV
E_0 = 22.2 GeV
$10^5\ A/Q^2\ (\mathrm{GeV}/c)^{-2}$
y
0
-5
-10
-15
-20
0
0.1
0.2
0.3
0.4
3-79
3579A2