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NEW RESULTS ON HIGH ENERGY ELECTROMAGNETIC INTERACTIONS*

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Just six months ago, a week-long conference on electromagnetic interactions was held in Liverpool. The proceedings of that conference[1] and the excellent reviews of electromagnetic interactions at other conferences last summer[2,3,4,5] relieve me of the obligation to attempt the impossible job of summarizing the work in the whole field. I will concentrate on three topics: Quantum electrodynamics, total photon-nucleon cross sections and electron scattering. Many of the present day experiments on these topics can be extended without difficulty to much higher energies using lepton and photon beams at NAL, whereas the observation and analysis of the two body (or quasi two body) processes in meson production (both vector and pseudoscalar) may well become more difficult with increasing energy. For example, the total γp cross section should be approximately 100 μb at very high energies, while, if the scaling

$$(s^2 - M^2)\,\frac{d\sigma}{dt} = k^2\,\frac{d\sigma}{dt} = \text{function of t only}$$

which describes pseudoscalar meson production between 3 and 20 GeV holds, (see Fig. 1) the cross sections, $d\sigma/dt$, for these processes will be the order of 10 nb.

1. Quantum Electrodynamics

Perhaps, the most important results dealing with electromagnetic interactions are the recent theoretical advances[6,7] in calculations to sixth order (α^3) for the low energy tests of Q.E.D. (Lamb shifts, hyperfine structure, and the g-factors of the electron and muon). These calculations, together with the value of α derived from experiments on the a.c. Josephson effect, have eliminated many of the puzzling discrepancies between theory and experiment.

The most serious remaining discrepancy appears to be in g-2 for the electron, where there is a discrepancy of 70 p.p.m. between theory and experiment, but

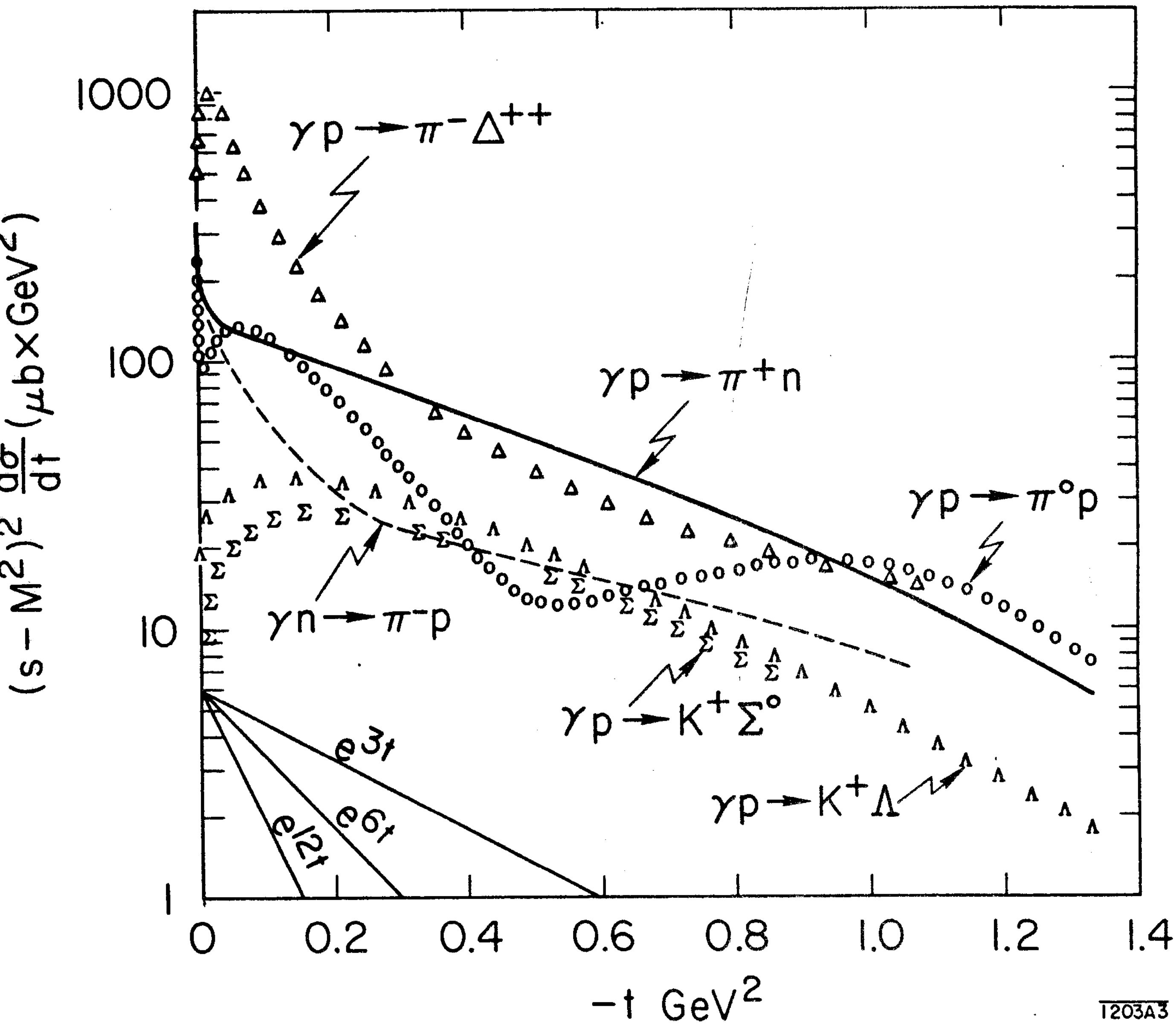

FIG. 1--Summary of cross sections for various two body photoinduced reactions assembled by R. Diebold.[3] By including the factor $(S-M^2)^2$, all data from ~3-20 GeV can be represented as shown.

there are still some higher order contributions to be calculated. It is interesting to note that many of the tests are at or near the limits where hadronic (and even weak!) interactions will have to be included.

In the high energy tests of Q.E.D., which are probably of more pertinent interest to this conference, there is also very little evidence of trouble. In Fig. 2, which is taken from Brodsky's talk at Liverpool,[1] the current limits on the various propagators are given, showing no evidence of breakdown at momentum transfers around a nucleon mass. In this diagram, the limits on photon propagators have been obtained using

$$\frac{1}{q^2} \longrightarrow \frac{1}{q^2} \pm \frac{1}{q^2 + \Lambda_\gamma^2}$$

and the limits on lepton propagators by

$$\frac{\sigma_{exp}}{\sigma_{th}} = \left(1 \pm \frac{m^4}{\Lambda^4}\right)$$

where m is the invariant mass of the final state ($m = m_{e^+e^-}$, or $m_{e\gamma}$, etc.).

The limits in Fig. 2 will no doubt be greatly increased using beams at NAL, and also in colliding beam experiments at Frascati and at the CEA, DESY, and SLAC where higher energy colliding beam facilities are underway.

On the subject of possible μ-e differences, the situation has changed little over the past couple of years. The calculations of Aldins et al.[7] referred to above, lead to a revised theoretical prediction for the anomalous part of the muon g-factor of

$$a_{theor} = (116587 \pm 3) \times 10^{-8}$$

to be compared with the CERN result[8] of

$$a_{exp} = (116616 \pm 31) \times 10^{-8}$$

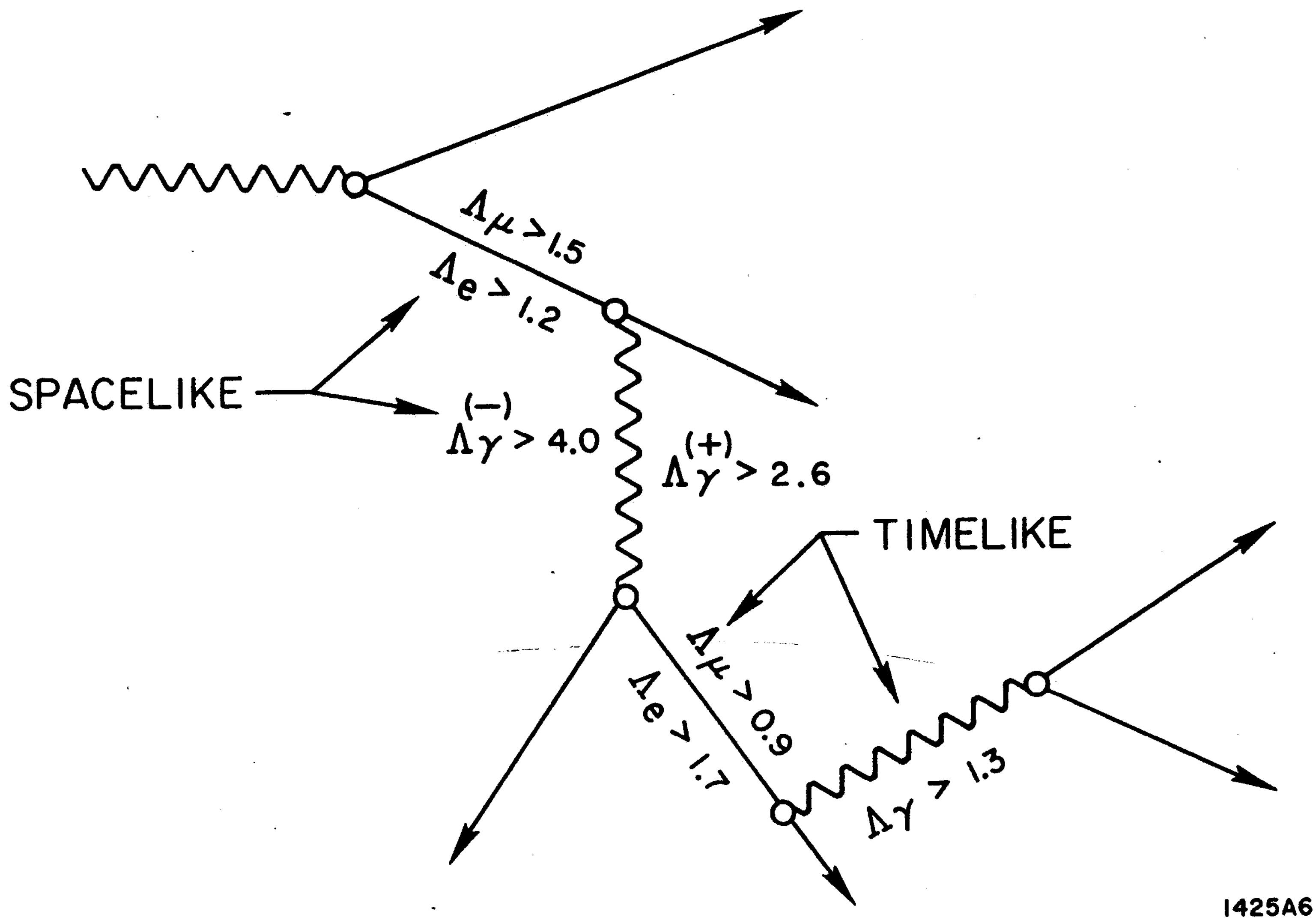

FIG. 2--Composite picture of high energy measurements with 95% confidence limits on possible modifications (in GeV) of the photon and lepton spacelike and timelike propagators. (See text for form of modifications assumed.)

A different test of μ-e universality can be made by comparing electron and muon results for scattering cross sections. There are weak indications of discrepancies in the present data.[9] The μ-p elastic cross sections appear to be somewhat lower in overall normalization than e-p cross sections, and there are preliminary indications that the SLAC inelastic μ-p may be following a similar trend.[10] It seems to me that there are many questions to investigate in both the electron and muon data before one can take the discrepancy very seriously.

In recent preprints[11] the Cambridge bubble chamber has reported some anomalies in the electromagnetic processes seen in an exposure of the 1.5 m British bubble chamber to a 1 GeV separated electron beam at the Rutherford.

The anomalies arise in three places:

1. The partition of energy between e^+ and e^- in pairs observed in the chamber does not correspond to the theory of Wheeler and Lamb. Figure 3a shows the distribution of events obtained. For $.3 < \frac{(p_+ - p_-)}{(p_+ + p_-)} < .6$ there appears to be an excess of events. This excess is around 60 events out of a total sample of ~ 3000.
2. In an exposure with 1.5 radiation lengths in front of the chamber, the distribution of p+ + p- for pairs observed in the chamber deviates from the expected γ spectrum as shown in Fig. 3b indicating more γ rays at $k = .8\ E_0$ than expected.
3. Bremsstrahlung of beam particles entering the chamber is observed to have a small excess at $E_{final} = .2\ E_{initial}$ as shown in Fig. 4.

The authors suggest that, if the effects are confirmed, they may have evidence for two new particles, with a charged particle having a mass of 10 - 60 MeV. This is all very recent, and it is not yet clear whether such particles could have avoided detection in other experiments. It is true that many previous mass searches would not have picked up a particle much lighter than a muon.

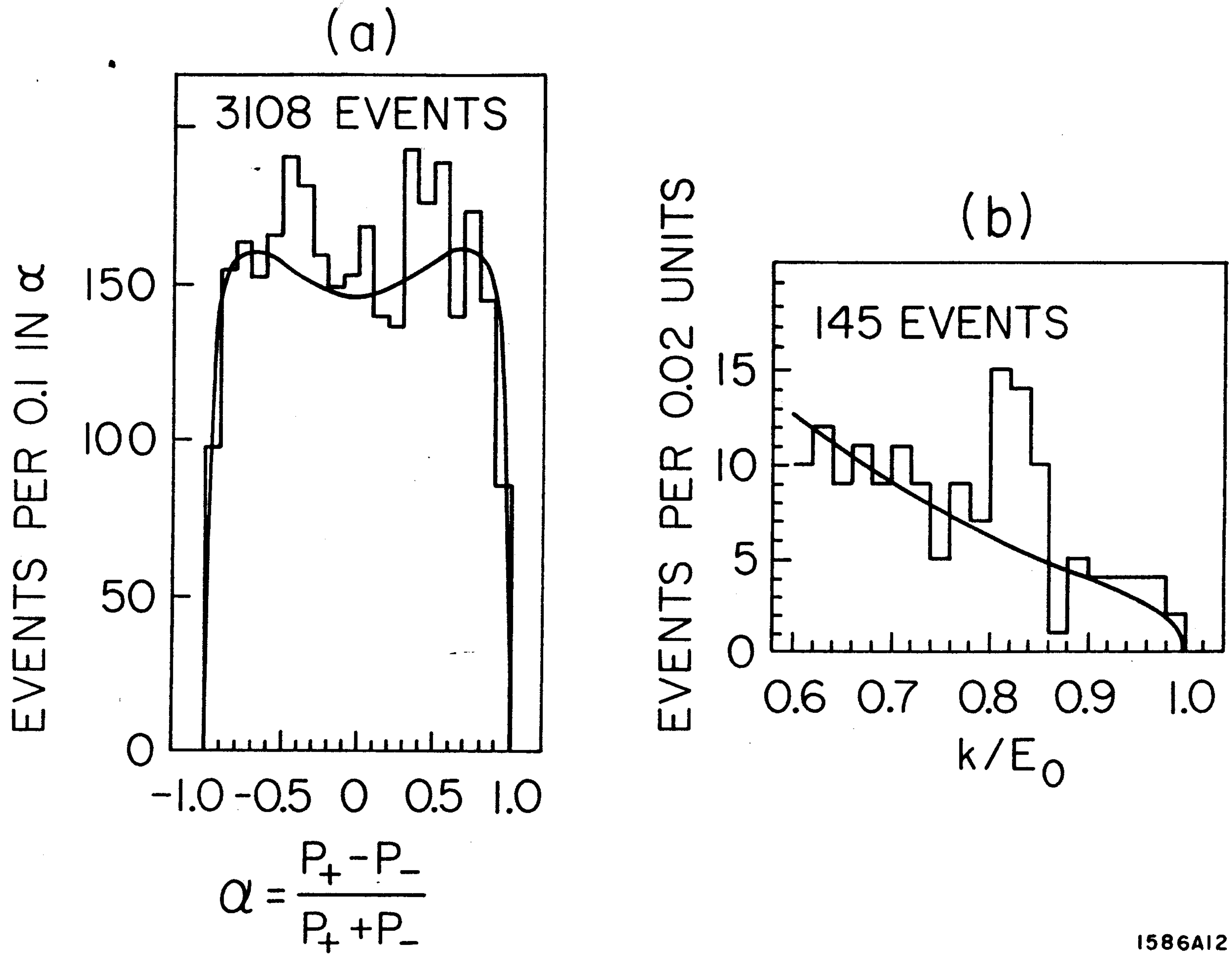

FIG. 3--Results from Cambridge Bubble Chamber Group. a) Distribution of partition of energy in pairs observed. b) Spectrum of pair energy for γ's produced with 1.5 radiation lengths in the beam.

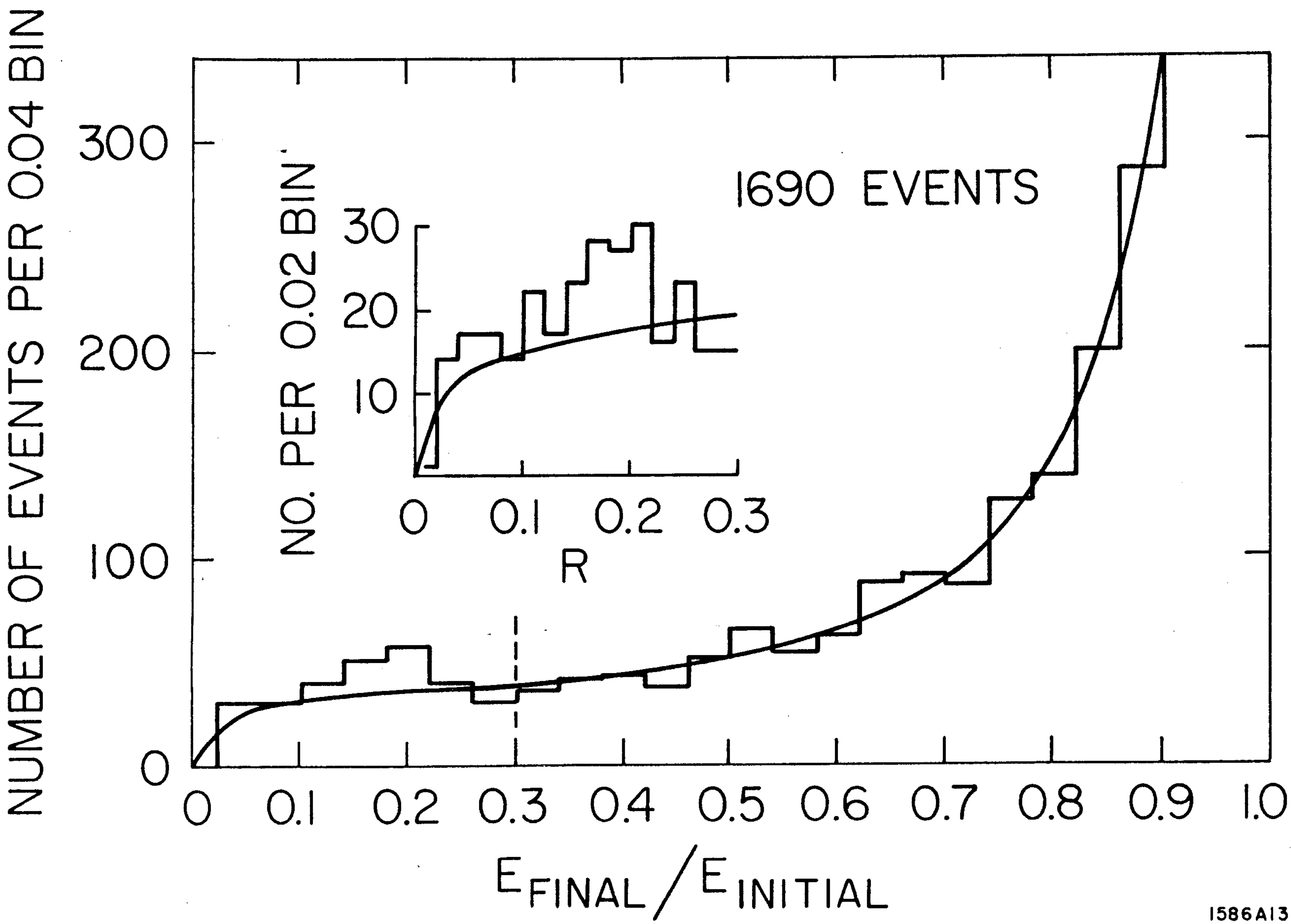

FIG. 4--Bremsstrahlung spectrum for events in the chambers. Fitted curves are normalized to the data excluding the anomalous regions.

Apart from this small cloud on the horizon, Q.E.D. continues to resist all onslaughts, and it will be interesting to see if the heavy artillery being constructed will be able to penetrate the imposing defenses.

There are also many tests of the invariance properties assumed by Q.E.D. Many possibilities exist which would be modifications rather than breakdowns of Q.E.D., and which would leave present results essentially unchanged. Bernstein, Feinberg and Lee[12] suggested that the observed CP-violation in κ decay might be a consequence of T-violation in electromagnetic interactions. Several experiments to test this hypothesis have already been completed and more are in progress. To the present time, there does not seem to be much solid evidence for T-violation. Table 1 summarizes the status of various tests. In Fig. 5, the results are shown of the recent LRL-SLAC experiment on inelastic electron scattering which has been submitted for publication.[13] A small asymmetry is indicated at a missing mass of about 1200 MeV in the $q^2 = 0.6$ data. It is difficult to find a reasonable physical explanation for this bump. The Christ-Lee[14] hypothesis would predict effects for $\Delta I=0$ resonances, but not for the $\Delta(1236)$ where isovector currents dominate. Tsai[15] has estimated two-photon exchange effects in this region and found them too small to account for the observed effect by about an order of magnitude. An effect of this size <u>somewhere</u> in the data of Fig. 5 has a statistical probability of approximately 1/10.

C invariance in electromagnetic interactions has been tested in experiments looking for asymmetry in the decay of the $\eta \longrightarrow \pi^+\pi^-\pi^0$ (assuming P and TCP conservation, this is equivalent to T-violation). Experiments have been done in both bubble and spark chambers. The most accurate value now quoted in the spark chamber experiments is that of Gormley <u>et al.</u>[17] who gives an asymmetry of $(1.5 \pm .5)\%$. Cnops <u>et al.</u>[18] find $(3 \pm 1)\%$.

TABLE 1

EXPERIMENT	AUTHORS	RESULT	COMMENTS
Neutron Electric Dipole Moment	J. K. Baird et al., Phys. Rev. 170, 1200-6 (1968)	$\mu_e / e < 5 \times 10^{-23}$ cm	Requires parity violation as well as T-violation for positive effect.
e d Elastic Scattering	R. Prepost et al., Phys. Rev. Letters 21, 1291 (1968)	$P_0 = 0.075 \pm .088$	$q^2 = .518\ (GeV/c)^2$
Weighted Asymmetry in $\Sigma_0 \rightarrow \Lambda + e^+ + e^-$	M. Bagget et al., Phys. Rev. Letters 22, 651 (1969)	$A = +0.014 \pm .021$	
$\gamma + d \rightarrow n + p$ vs $n + p \rightarrow \gamma + d$	B. L. Schrock et al., Phys. UCRL 19350, Sept. 1969; D. F. Bartlett et al., PPAR 20, (1969)	Possible effect	Experiments quoted are $n+p \rightarrow \gamma+d$. Both see slight difference in angular distribution, compared with inverse reaction at $T_n \approx 575$ MeV.
Christ-Lee Experiment e-p Inelastic Scattering	J. R. Chen et al., Phys. Rev. Letters 21, 1279 (1968)	Consistent with no T-violation	$W_2 = 1.1 \rightarrow 1.7$ GeV $q^2 = .2 \rightarrow .7\ (GeV/c)^2$
	S. Rock et al., Phys. Rev. Letters 24, 748 (1970)	Consistent with no T-violation	$W = 1.1 \rightarrow 2.5$ GeV $q^2 = .4 \rightarrow 1\ (GeV/c)^2$

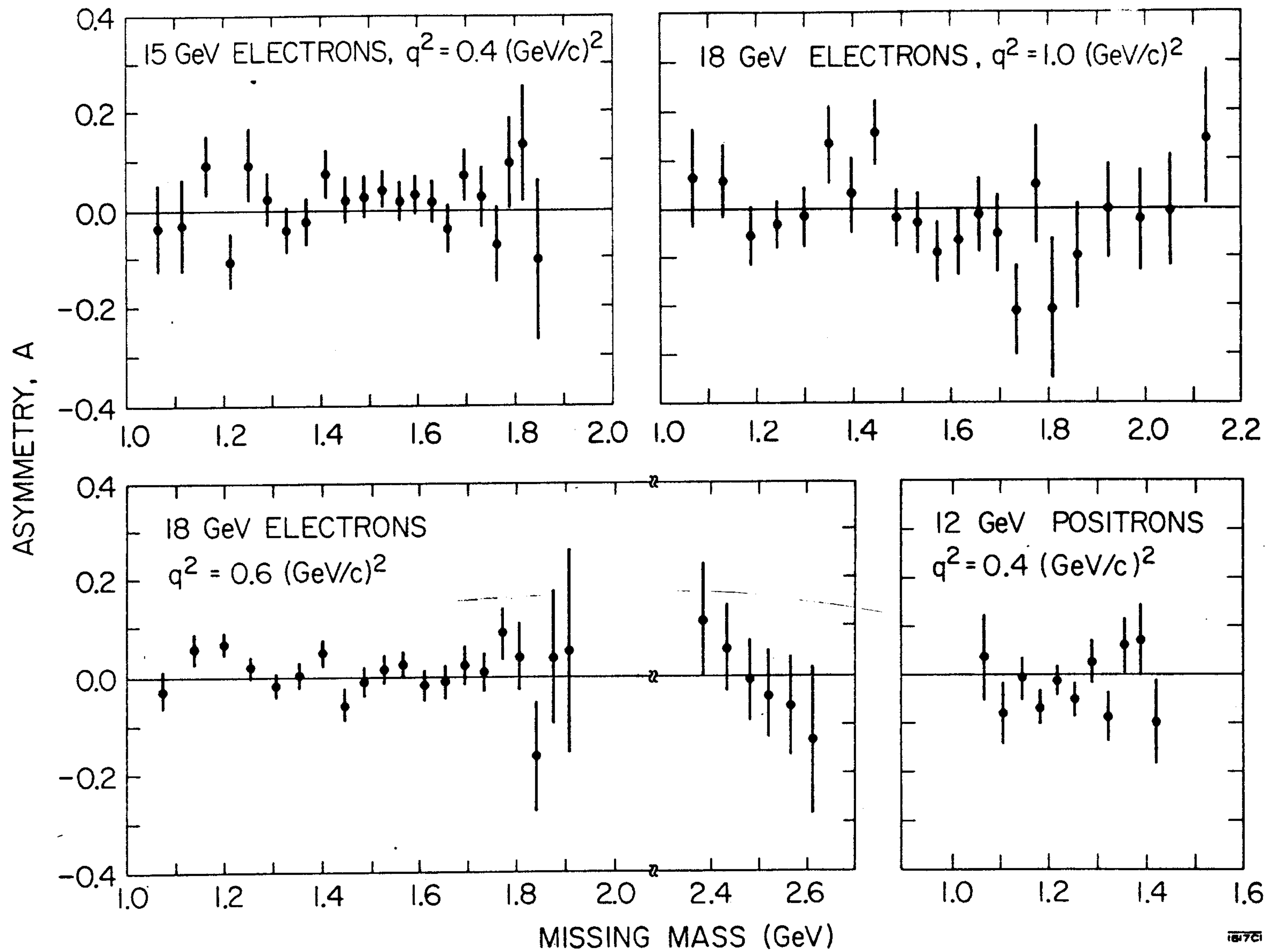

FIG. 5--Results of the recent LRL-SLAC experiment on inelastic electron scattering.

The bubble chamber results[18,19,20,21] are based on considerably smaller number of events and the measured asymmetries show a tendency to scatter rather more than the statistics would indicate.

P invariance in electromagnetic interactions has received relatively little attention from high energy physicists. Nuclear physics experiments[22,23] have pushed down to levels where weak interaction effects are expected, showing that P conservation is good for real photons to about 1 part in 10^5. In experiments designed to measure two-photon exchange effects by observing polarization of recoil protons, the polarization observed at right angles to the expected effect can be used to set limits on P-violation for "off the mass shell" photons. No asymmetry is observed at the few percent level for $q^2 \approx .8\ (\mathrm{GeV/c})^2$.[24,25]

2. Compton Effect and Total Cross Sections

The Compton effect for nucleons is a fundamental experiment which has become notorious for its difficulty. There are experiments in progress at DESY, CEA and SLAC. In January, the SLAC (Group F) - Northeastern collaboration completed an experiment for τ values between 0.1 $(\mathrm{GeV/c})^2$ and 1 $(\mathrm{GeV/c})^2$. The experiment measures coincidences between the recoil proton and the scattered γ ray. Figure 6 shows the clean separation obtained between Compton photons and photons from π^0 production. The results of this experiment will soon be available. The experiment at DESY covers a range of slightly smaller τ and is also very close to completion. As with the SLAC data, they have demonstrated a clean Compton signal. Another SLAC (Group C) experiment is planned for later this Spring which will concentrate on lower τ ($< .3\ (\mathrm{GeV/c})^2$) measurements.

The optical theorem relates the imaginary part of the forward Compton scattering to the total photoabsorption cross section so that in a short time it should

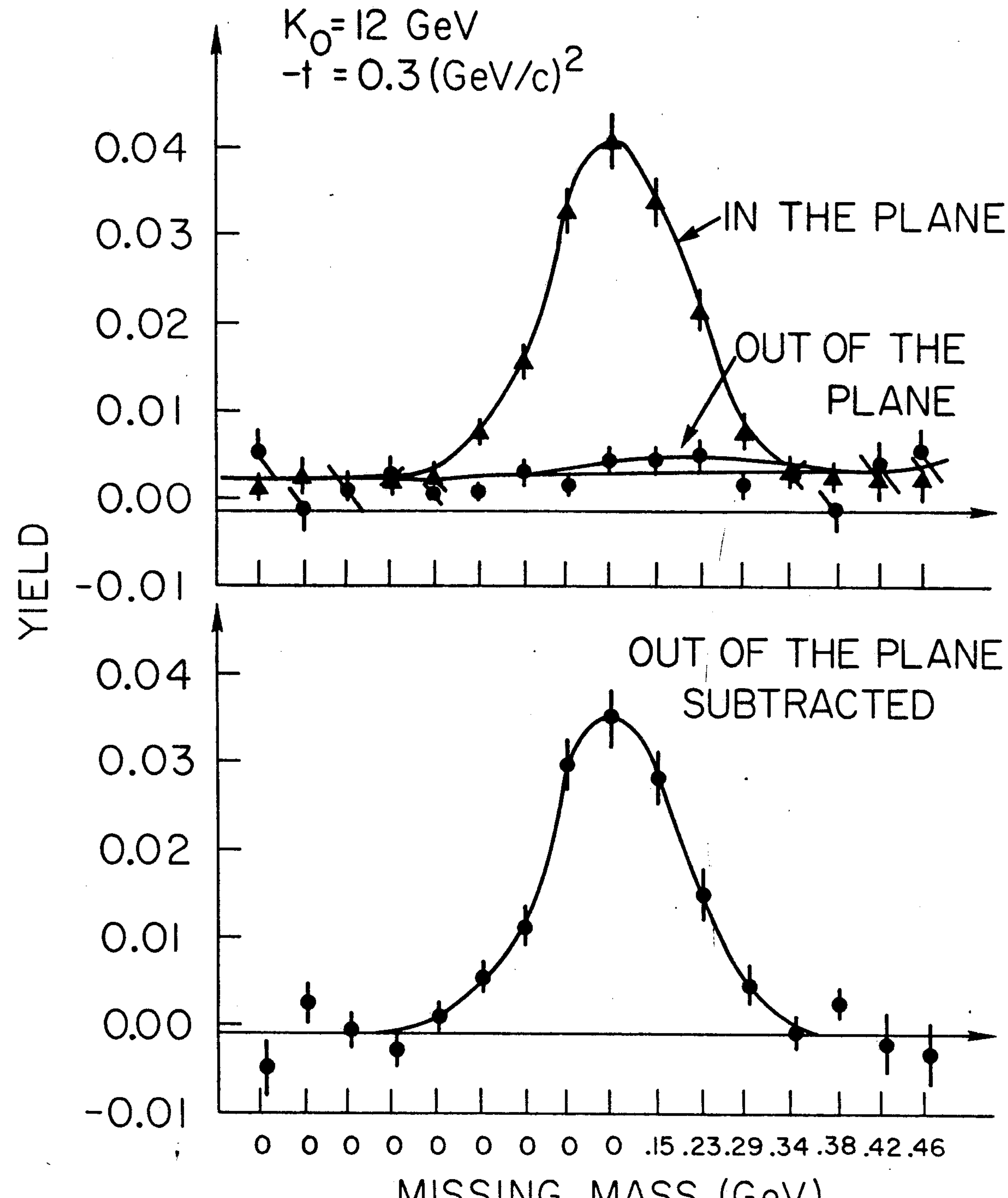

FIG. 6--Raw data from Compton scattering experiment by the SLAC-Northeastern collaboration. The yield of coincidences between a spectrometer detecting recoil protons and a shower counter detecting scattered γ-rays is shown when the shower counter is placed in or out of the scattering plane, as defined by the spectrometer. The Compton signal is quite clearly separated from other processes, such as π^0 production.

be possible to test the oldest of the dispersion relations. The data will also provide a very straightforward comparison between the τ dependence of this process and ρ production.

There has been a considerable increase in the amount of data on total photo-absorption cross sections in the past years or so. The data is summarized in Fig. 7. In this plot, there is bubble chamber data, counter data, both domestic and imported, taken in tagged photon beams, and finally data obtained by the MIT-SLAC collaboration. This data is obtained by extrapolating e-p inelastic scattering data taken at 1.5^{o} to $q^2 = 0$, and the points do not show the systematic errors estimated to be about 10%. This extrapolation technique may be especially suitable for studies of the resonance region, particularly if the systematic errors can be reduced.

The solid line on the figures is an average of π^+p and π^-p cross sections multiplied by a "normalization" factor of 1/200. Excepting the region near the second resonance the similarity in energy behavior is striking, especially the slow fall off at high energies. Using a fit of the form

$$\sigma_t(\nu) = C_1 + \frac{C_2}{\sqrt{\nu}}$$

Damashek and Gilman[26] find the suggestion of an extra constant in the dispersion relation given by Creutz, Drell and Paschos[27] which is consistent in sign and magnitude with the value of the Thomson limit, $-\alpha/M_n$. More accuracy is needed both in the present energy region and in the region made available at Serpukhov and NAL to establish firmly the existence of this "fixed pole."

Total cross sections on the neutron are obtained by the tagged photon beam experiments at both DESY[28] and the Santa Barbara at SLAC.[29] The neutron cross sections are found to be a few percent smaller than the proton cross sections

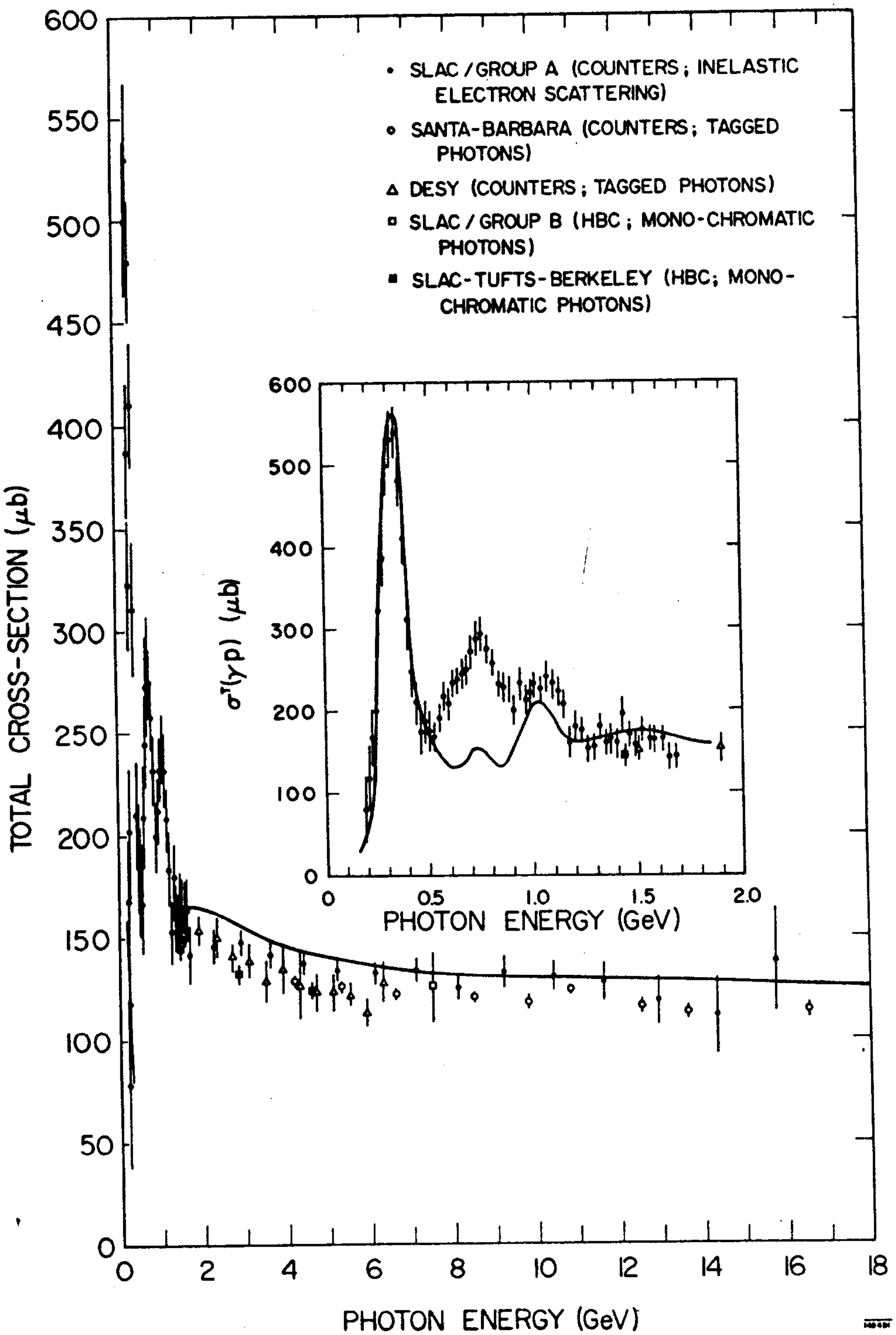

FIG. 7--Energy dependence of the total photon cross section on the proton. The solid line is 1/200 of the mean of π^+p and π^-p total cross sections.

for k > 2 GeV. The A-dependence of the total absorption cross section has also been measured[29] and found to vary approximately as $A^{.9}$.

Quantitative comparisons of the A-dependence with vector meson dominance are somewhat confused by the discrepancies between DESY,[39] SLAC-LRL,[31] Cornell,[32] and Rochester[33] experiments on ρ photoproduction from complex nuclei. According to Fig. 8 the DESY data is consistent with the $A^{.9}$ behavior, and presumably this will also be true for the new Rochester data.

Qualitatively, the nonlinear dependence on A is taken as verification of the Stodolsky[35] suggestion that the photon would be "shadowed" like the ρ in nuclei and would show an A-dependence which is inconsistent with that expected from the photon's mean free path in nuclear matter as estimated from the γp cross sections.

Experiments of this kind will be quite feasible at the intensities expected for electron beams at NAL as the cross sections are dropping very slowly with energy.

3. Electron Scattering

The form factors in the Rosenbluth equation can be roughly represented as follows

$$G_e^p = \frac{G_m^p}{\mu_p} = \frac{G_m^n}{\mu_n} = \frac{1}{(1+q^2/0.71)^2} \quad , \qquad G_e^n \approx 0$$

where q^2 is expressed in units of GeV/c. All laboratories agree that there are deviations from the dipole formula for G_m^p which is the most accurately measured of the form factors. The ratio $\left(G_m^p/\mu_p\right)/(1+q^2/0.71)^2$ falls a few percent below 1 between $q^2=0$ and 1 $(\mathrm{GeV}/c)^2$, then rises a few percent above 1 between $q^2=1$ and ~ 5 $(\mathrm{GeV}/c)^2$, and finally falls to about .85 by 20 $(\mathrm{GeV}/c)^2$.

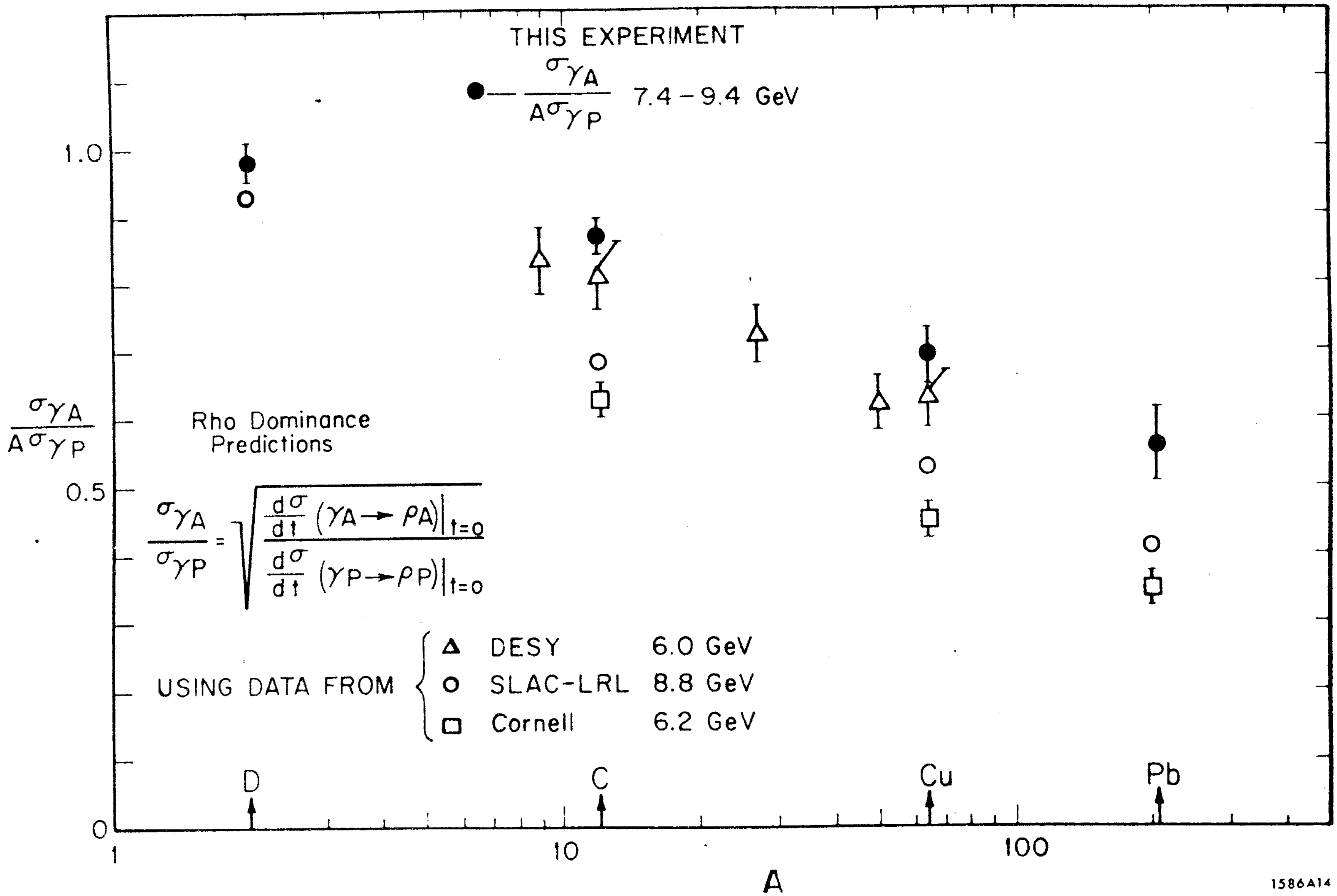

FIG. 8--Total photoabsorption cross sections for photons between 7.4 and 9.4 GeV, as a function of A. For comparison, the predictions of ρ dominance are shown, based on data from DESY, SLAC-LRL and Cornell.

In a very elegant experiment at DESY,[36] e-p and e-n scatterings have been measured simultaneously from D_2 with the same apparatus, and the ratio of e-p to e-n coincidences obtained. They have sufficient data to check the effects of binding energy by plotting ratios of experimental result to Durand's[37] theory as a function of spectator kinetic energy. The quantity, G_m^n/μ is found to be within 5% of scaling for several q^2, all below 1 GeV/c^2. G_e^n is small and consistent with zero in this data and remains the least well measured of the 4 form factors, for obvious reasons.

Bonn[38] has presented evidence that shows G_e^p falling faster with q^2 than G_m^p/μ_p for $1 < q^2 < 2\ (GeV/c)^2$, Fig. 9 . The effects are not very large but are statistically significant.

Since there were never very clear reasons why the dipole expression or the scaling laws existed one cannot feel much pain over the fact that the relations appear to be only approximate.

Personally, I feel that the higher energy, lower intensity electron beams which may come from the new proton synchrotrons will not be of great value in the study of elastic form factors since one already can work at very small angles, and accuracy rather than energy seems to be the major limitation at present. Projected NAL beam intensities will make it very difficult to extend the range of q^2 beyond present measurements. There is, however, one obvious measurement which can be done well with energies on hand at Serpukhov and, of course, even better at NAL. This is the pion form factor. At ≈ 100 GeV π-e scattering would correspond to the scattering of ~ 400 MeV electrons off π's at rest, which is quite adequate to measure the π radius accurately and probably enough to differentiate between $1/q^2$ and $1/q^4$ behavior in a precision experiment. For κ mesons at 100 GeV the equivalent electron lab energy is about 100 MeV.

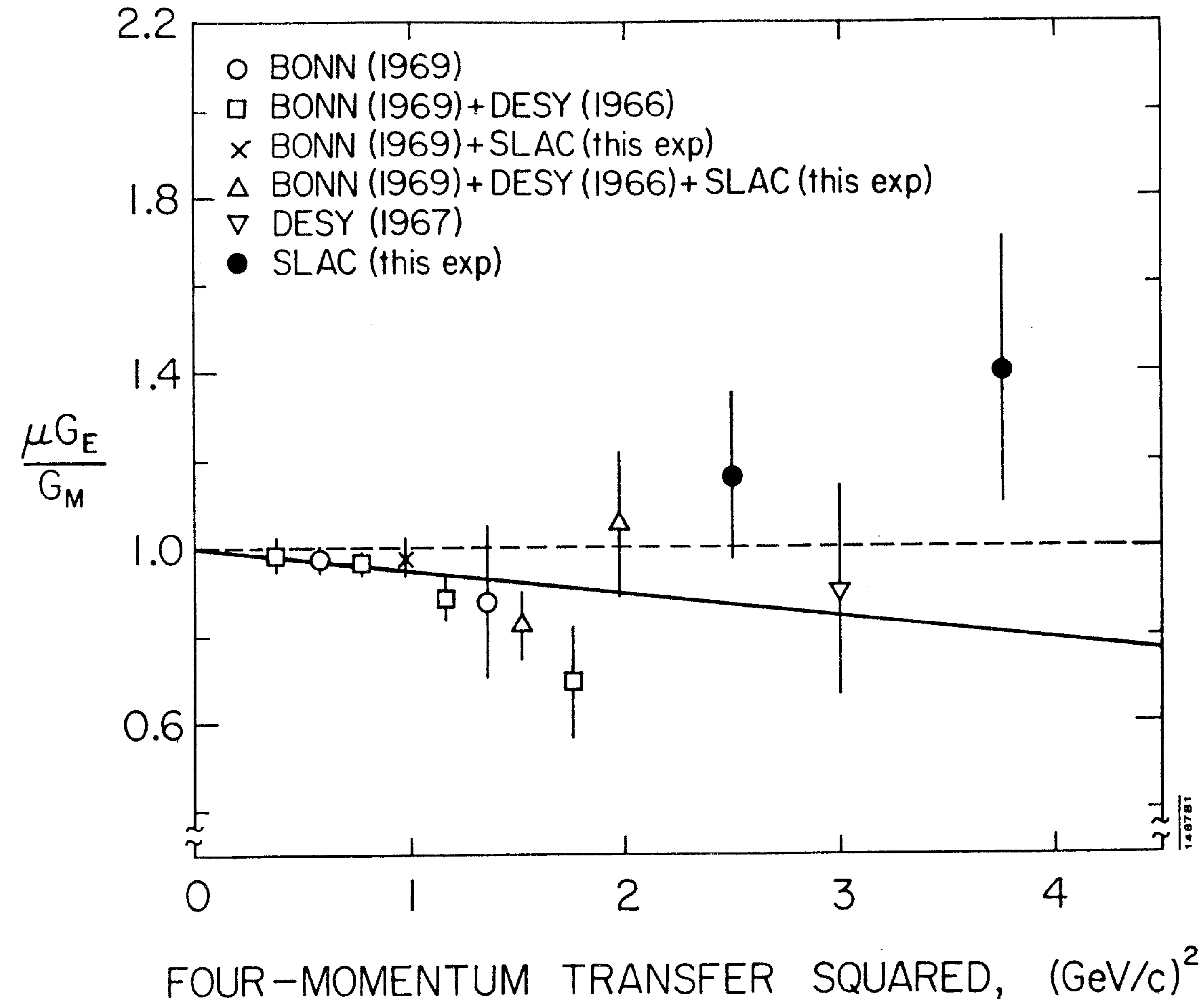

FIG. 9--Ratio of $\mu G_e/G_m$ for various momentum transfers. The best fit to all data shows a statistically significant deviation from scaling.

Measurements of the inelastic proton form factors continue at all the high energy electron accelerators. There are two major topics of interest: the excitation of resonances, and the scattering at large ν (energy loss) and q^2 (4-momentum). Resonance production is observed at values of $q^2 \lesssim 3\ (\mathrm{GeV}/c)^2$, and the experiments are only beginning to tap the wealth of information available. Single arm experiments have been done extensively, and the resonance cross sections show a high q^2 dependence similar to elastic scattering. Coincidence experiments have already begun at several laboratories, and interesting results are already available from CEA and DESY groups.

In the so-called "deep" inelastic region, data has been published by both DESY[39] and MIT-SLAC.[40] Following the initial observation of the slow q^2 fall-off of the cross section for W (invariant mass of the final state) > 2, several experimental questions have arisen:

1. Separation of the form factors;

The cross section can be expressed as,

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2(E')^2}{q^4}\left[W_2(\nu,q^2)\cos^2\theta/2 + 2W_1(\nu,q^2)\sin^2\theta/2\right]$$

or

$$= \frac{\alpha}{4\pi^2}\ \frac{\kappa}{q^2}\ \frac{E'}{E}\left(\frac{2}{1-\epsilon}\right)(\sigma_T + \epsilon\sigma_L)$$

where, with $q^2 = 4EE'\sin^2\theta/2$, and $\nu = E-E'$,

$$\kappa = \nu - q^2/2M_n$$

and

$$\epsilon = \frac{1}{1+2(1+\nu^2/q^2)\tan^2\theta/2}$$

W_1 and W_2 (or equivalently σ_L and σ_T) can be separated by making measurements for a single q^2 at several angles, just as in the case of the elastic form factors.

2. Possibility that νW_2 and W_1 are functions of (ν/q^2) only (scaling).
   Behavior consistent with the scaling predicted by Bjorken[41] was observed for the low angle data, provided that σ_L/σ_T is small (Fig. 10).
3. Behavior of neutron scattering cross sections.
   Diffractive models (including VDM) for the process would require σ_n and σ_p to be equal for high ν.
4. A-dependence of scattering cross sections.
   $\sigma_T(\nu, q^2)$ is the total absorption cross section for virtual photons on the nucleus. As q^2 increases, the "shadowing" effect seen for real photons should disappear.[42]
5. What comes out the other side?
   Various models predict different distributions of particle momentum in the hadronic system. Coincidence measurements will be very helpful. Experiments are underway at DESY, Cornell and SLAC.

A group at DESY[39] using cross sections measured at 48^o and the 6^o and 10^o forward angle data from the MIT-SLAC collaboration obtained values of σ_L/σ_T considerably less than 1 (Fig. 11). Preliminary results from the MIT-SLAC data at 18, 26, 34^o are in agreement with this result (Fig. 12). The possibility of systematic differences between forward and backward angle data has led us to quote $\sigma_L \leq \sigma_T/2$ until a final analysis of the large angle data is completed. Such a low value of σ_L/σ_T does not agree with a straightforward application of VDM,[42,43] but questions about the domain of validity of this application have

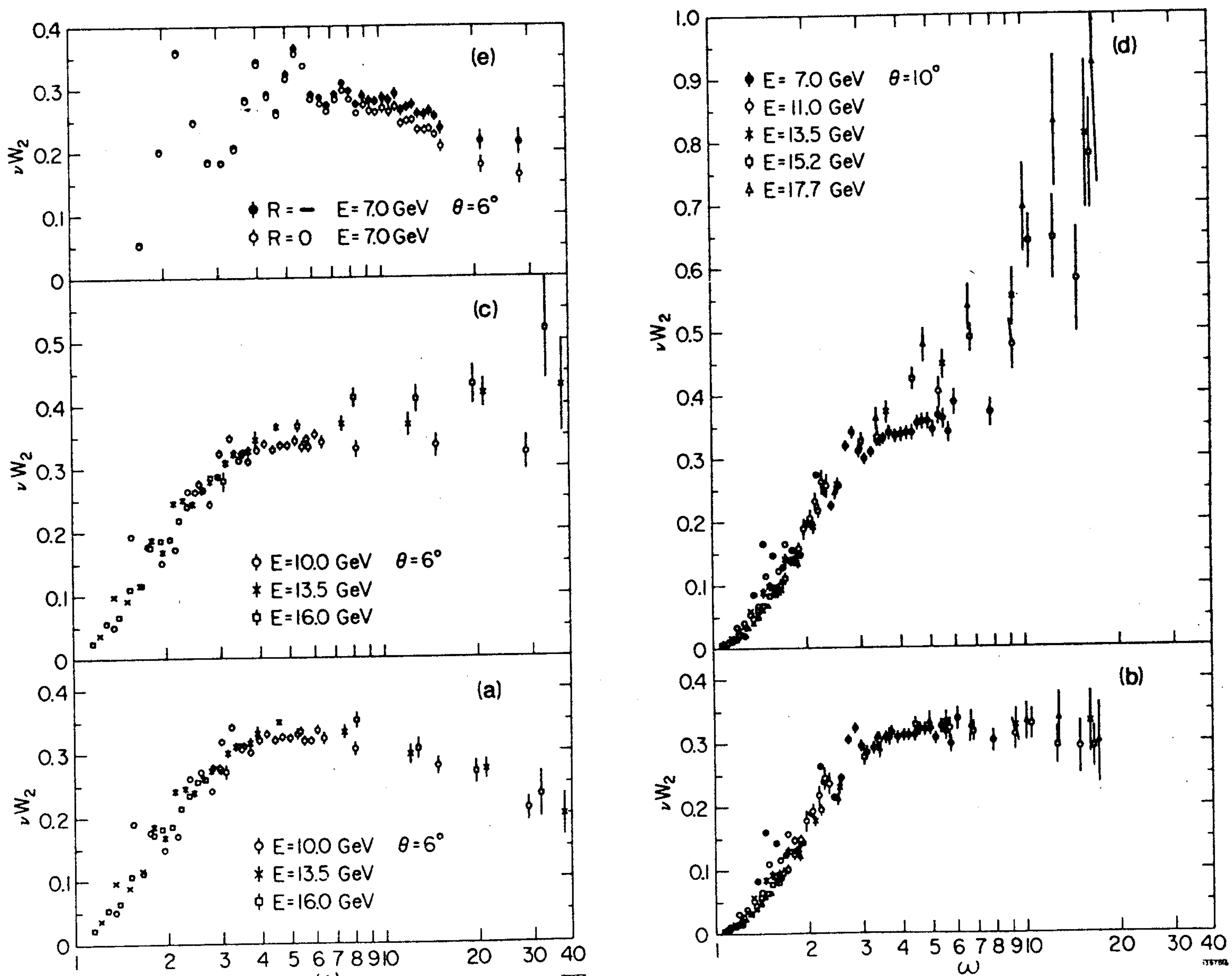

FIG. 10--Values of νW_2 vs $\omega = 2M\nu/q^2$: a) for $\theta = 6^o$, $E_0 = 10$, 13.5, 16 GeV assuming $\sigma_L/\sigma_T = 0$; b) for $\theta = 10^o$, various energies, assuming $\sigma_L/\sigma_T = 0$; c) same data as a), but assuming $\sigma_T/\sigma_L = 0$; d) same data as b), assuming $\sigma_T/\sigma_L = 0$; e) for $\theta = 6^o$, $E_0 = 7$ GeV. The q^2 in this data are small, and scaling is not expected to hold.

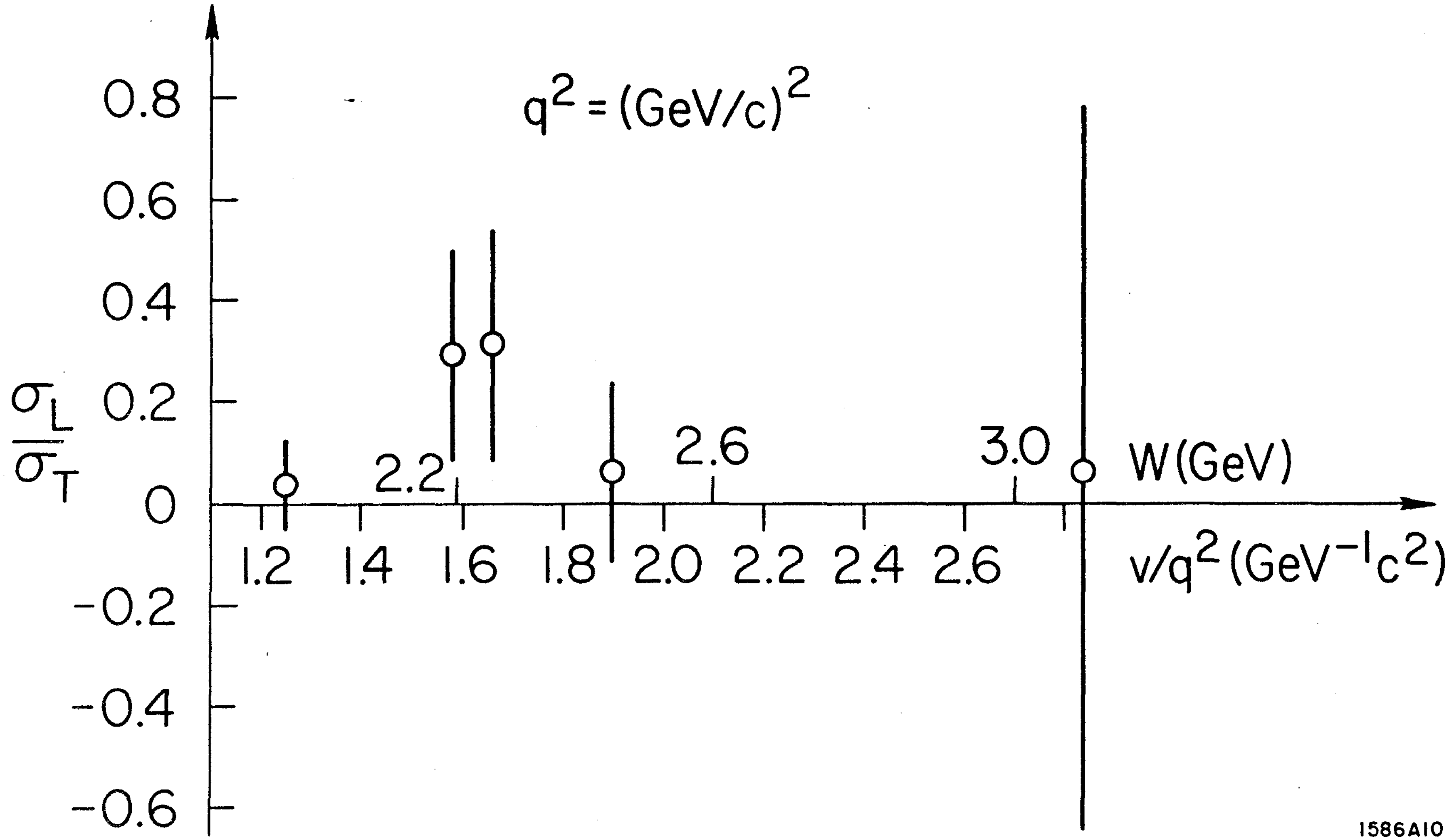

FIG. 11--Separation of the inelastic form factors σ_L and σ_T as a function of four-momentum transfer, using DESY data at 48^o and MIT-SLAC data at 6^o.

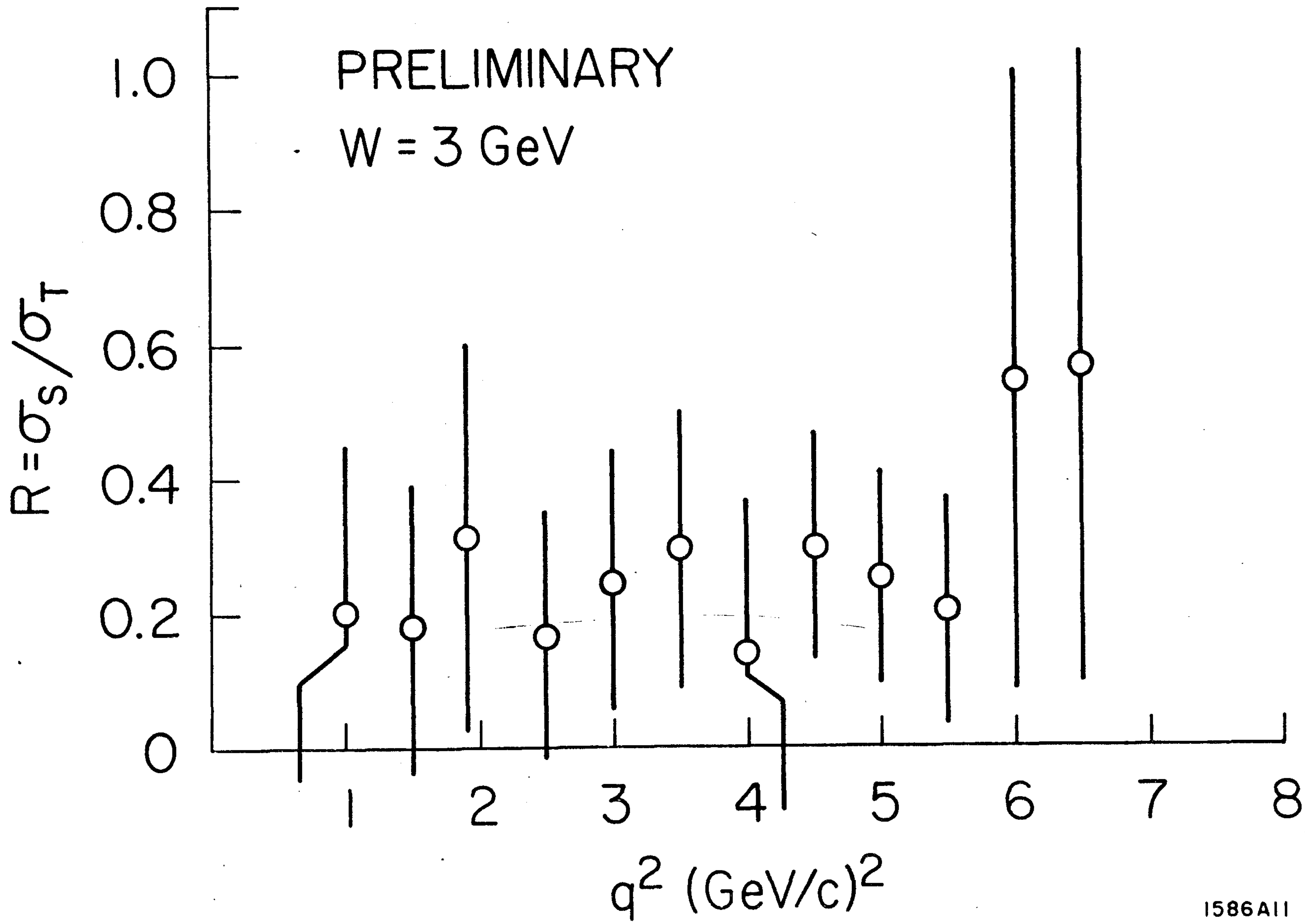

FIG. 12--Separation of σ_L and σ_T as a function of q^2, using MIT-SLAC data at 6^o and 10^o and preliminary data at large angles.

been raised.[44,45] More general diffraction schemes[46] to explain the weak q^2 dependence are not necessarily troubled by this low ratio of σ_L/σ_T. However, a general feature of any diffraction model is the equality of n and p cross sections at high ν.

The possibility of scaling was suggested by Bjorken before the measurements were made. With a small value of σ_L/σ_T, the relation seems to be satisfied within errors. Nauenberg[47] has reached other conclusions by fitting analytic functions to the cross sections and finding coefficients of terms other than (ν/q^2) significantly different from zero. He does not appear to have considered the systematic errors quoted, nor is it clear what would happen if higher order polynomials were used in the fits. It is my feeling that his fit is a possible parameterization of the data, but that scaling is certainly not excluded at present.

We have some preliminary data from 18, 26, 34^0 shown in Fig. 13 for three values of $R = \sigma_L/\sigma_T$ which shows that the cross section behaves in a manner consistent with scaling, within the accuracy of the data at these higher angles.

The MIT-SLAC collaboration has just completed measurements of the ratio of deuterium to hydrogen cross sections at 6^0 and 10^0, and in addition have measured cross sections for Be, Cu and Au. After some months of work we should be able to shed some light on the neutron cross sections and the A-dependence.

High energy lepton beams at Serpukhov and NAL can greatly extend the range of measurement in ν and possibly in q^2 if the intensities are sufficiently high. Because of the smaller radiative corrections, muon beams are likely to be more useful than electron beams of comparable intensities. If, by the time these beams are operational, the lower energy data does not exclude, or even supports, the

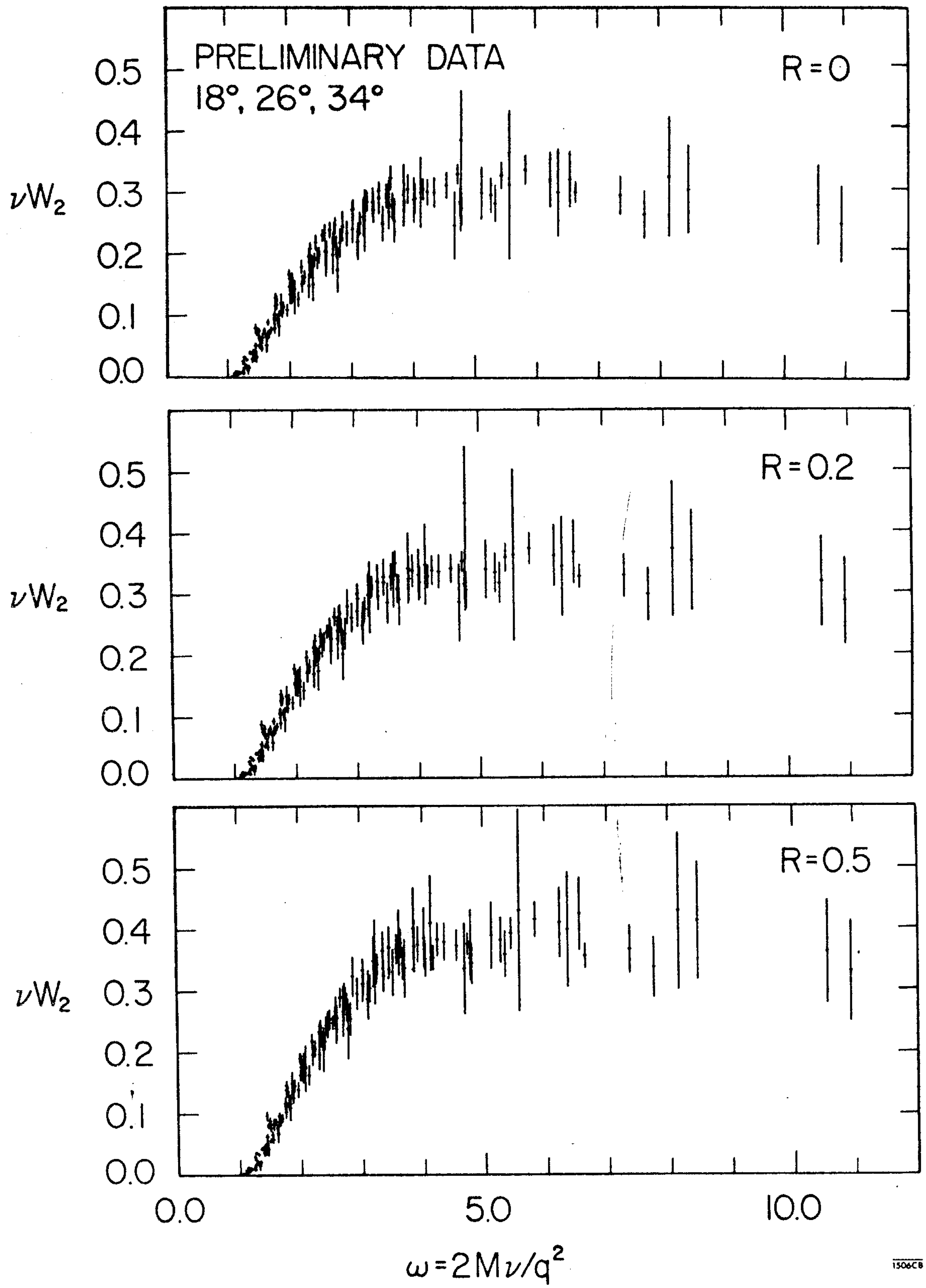

FIG. 13-- νW_2 for preliminary MIT-SLAC data at 18°, 26°, 34°, for various values of $R = \sigma_L/\sigma_T$. Compare with Fig. 11.

the hypothesis of nucleon sub-structure, the experiments will no doubt enjoy a high priority.

In conclusion, it is evident that there are many important experiments to be done with the lepton and photon beams at the proton synchrotrons. A fair number of these experiments will have very respectable cross sections and will be relatively easy to perform. However, I should warn those interested that studies are now underway at SLAC with a view towards a superconducting conversion, which might result in present SLAC currents at ~ 100 GeV, with a 10% duty cycle.[48]

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