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KNOWN AND UNKNOWN REGIONS IN LEPTON PHYSICS*†

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I. Introduction

Ancient explorers in search of distant lands and treasures had no idea how great the challenge or how difficult the passage, or how rich the treasures they sought. They sailed into uncharted seas. Their only scale of distances came from previous journeys starting from ancient Phoenicia and extending to Crete, and through the Mediterranean to the North Sea.

This year marks the 10th anniversary of the birth of this series of high energy photon electron conferences, and we can today look back with the ancient mariners and view how far we have progressed during the past decade in our explorations on the lepton frontiers of nature. We can map out where we have been and mark the boundary between known and unknown regions.

A two dimensional projected map for electromagnetic explorations is plotted in terms of the invariant momentum transfer q^2 carried by the local electromagnetic current operator that probes the hadron and of the energy transfer $M\nu \equiv p\cdot q$ or of the total hadronic mass produced $W^2 \equiv (p + q)^2$. Ten years ago[1] this map had been explored only in the "southern latitudes", and then only along its nearby shores as shown in Fig. 1. Elastic scattering studies of proton form factors extended to $-q^2 \lesssim 2$ GeV^2 and inelastic electropion production probed up to $-q^2 \sim 1/2$ GeV^2 and to hadronic masses W^2 in the neighborhood of the 33 resonance. Photoproduction studies extended through the resonance region $W^2 \lesssim 3.3$ GeV^2. Not only were the distant shores of high q^2 and W^2 yet to be probed but the mysterious ominous depths far from both the q^2 and W^2 shores were unexplored; and of course the "northern latitudes" of time-like $q^2 > 0$ were just opening to inquiry as the first generation of colliding rings at Orsay, Novosibirsk, Frascati, and Stanford stored and collided their electron and positron beams.

New theoretical ideas discussed at that first conference ten years ago included Reggeization of processes with photons as external lines - viz. photopion production or Compton scattering from hadrons - and Reggeization of internal photon lines leading to modifications of quantum electrodynamics (QED); the possibility of diffraction production of vector mesons by high energy photons; the Primakoff effect; and the photoproduction of heavy vector mesons ($W^{\pm}$).

Experimentally the properties of the η mesons were confirmed and clarified by photoproduction studies. QED was confirmed at the 1 GeV momentum scale, or down to distances of a few tenths of a fermi by precision experiments at low energies (in particular by precision g-2 measurements) and by high energy wide angle pair production measurements, though difficulties with the hyperfine structure and Lamb shift comparisons were not yet resolved. It had also not yet been established to what extent the photons interacting peripherally were prodigious producers of hadron beams.

Now ten years later we are far from the shoreline of the $q^2 - W^2$ map. But just as Columbus couldn't predict the distance to America from the known distance between Mediterranean ports of call we don't know how far it is to possible thresholds of exciting new physics. We do know that the frontiers of quantum electrodynamics have been pushed forward yet another decade. This is the 20th Century parallel to Newton's great advance of a universal theory of gravitation 300 years ago. We now know the theory of Dirac and Maxwell - plus the Feynman-Schwinger-Tomonaga renormalization procedure - surmounts all experimental challenges down to scales of distance $\sim 10^{-15}$ cm. Professor Strauch[2] reviewed the impressive new progress in high momentum transfer electrodynamic processes using colliding rings; the precision tests from hydrogen atom spectroscopy and electron (g-2) values all agree very well with theory.[3] Since space probes confirm the classical Maxwell-Faraday theory out to $\sim$ 80 earth radii by measurements of the earth's magnetic field we can say that we indeed have a truly universal electromagnetic theory valid over a scale range of 25 decades.

So at this conference ten years later we have moved away from the shores in establishing Bjorken scaling; we have entered northern latitudes with high energy, high luminosity colliding rings; we have begun to move out of the $q^2 - W^2$ plane;[4] it is the ρ' that plays the role of the η in the 1963 conference. Our electromagnetic probe - our sailing vessel - is understood; i.e., fortunately it <u>doesn't</u> Reggeize yet. In the past year it has been joined by a very exciting sister ship - the neutrino probe; and now we ask where - if indeed anywhere - are those distant shores.

Abandoning this nautical metaphor and returning to technical language we want to know simply:

> Is scaling here to stay or is it an approximate, transitory phenomenon?
>
> Can we identify properties of the hadronic <u>constituents</u> and establish the hadronic structure in terms of quarks or partons by observing the hadronic <u>debris</u> from deep inelastic events?

What deeper understanding can we gain from probing the multiplicities and detailed reaction patterns as a function of q^2 and W^2, and from analyzing the fragmentation and central plateau regions as well as scaling laws for the emerging hadrons?

In our first detailed glimpses of the time-like region of momentum transfers what happens to scaling and how is the observed structure related to the scattering observations?

A new scale of masses or energies has entered this field along with extremely important new theoretical ideas which offer the hope of unifying the weak and electromagnetic interactions - i.e., the gauge theories. This scale is given by the ratio associated with the mass of the presumed heavy vector meson $M_W \sim \sqrt{e^2/G} \sim 37$ GeV. Whether this scale also has anything to do with the hadronic world is an entirely open question at this time. But the exciting prospect beginning to form before our eyes is the vision of the entire world of the weak interactions of the leptons with hadrons; and already the $q^2 - W^2$ map is being charted now with neutrinos[5] as well as electrons.

In a decade our progress is enormous but the vistas are more exciting than ever.

II. Scaling in Electromagnetic Processes

The observed scaling behavior for deep inelastic electron scattering suggests that hadrons may be composed of point-like spin-1/2 constituents (partons) from which the virtual photon scatters incoherently. In configuration space, one assumes that the virtual photon is probing the leading light-cone singularity of the current commutator; i.e., one assumes typically that the current is probing with high resolution the asymptotic short distance structure of the internal constituents of the nucleon. The picture seems almost too good to be true, in that the onset of this presumably asymptotic phenomenon occurs[6] for surprisingly small values of the mass $\left(\sqrt{Q^2} \equiv \sqrt{-q^2}\right)$ and laboratory energy (ν) of the virtual photon, $\gtrsim$ 1.5 GeV. Moreover we don't directly see these constituents - or we cannot recognize them if we do because of the very strong binding forces from which they are released upon emerging as the debris from smashed nucleons. Nonetheless, it is tempting to proclaim that we have glimpsed the elementary, structureless building blocks from which hadrons are constructed; that nothing remains between us and the light cone. In this case scaling will remain valid as we probe with larger and larger values of ν and Q^2. This view is reminiscent of that of classical physicists extrapolating the classical theory of specific heat to zero temperature. With no microscopic energy scale, $C_v = 5/2\ R$ for diatomic molecules and is predicted to be a constant independent of T. In fact however at low enough $T \to 0^{\circ}K$, degrees of freedom are frozen as kT falls below vibrational and rotational excitation energies which provide the new energy scale.

Consider a less exuberant perspective on the meaning of scaling:[7] that it represents the exposing of just another layer of matter, and the observed scaling reflects the preasymptotic behavior of a coarse probe to which the constituents appear to be point-like. Such a view is old-fashioned in that it anticipates the repetition of a story which has occurred in other areas of physics.

Phenomena very similar to the scaling in electron-nucleon scattering have been observed previously in the scattering of electrons from atoms and from complex nuclei. Nuclei are particularly interesting in this respect. For virtual photons with $Q^2 \lesssim (300 \text{ MeV})^2$ individual nucleons in the nucleus scatter coherently and the resonant level structures of the nucleus are displayed. But already at $Q^2 \cong (400 \text{ MeV})^2$ the coherent excitations have essentially disappeared and the cross section is dominated by <u>incoherent</u> scattering from individual nucleons and by the quasi-elastic peak, which occurs at $Q^2 \cong 2M^*\nu$, with M^* the effective proton mass as shown[8] in Fig. 2. This is in fact similar to the scaling seen in the electron-nucleon case, except that in the nuclear case the would-be scaling is violated by the production of pions and by the nucleon form factors which vary with Q^2. [Note that $G_M^2([400 \text{ Mev}]^2) \approx 1/2$.]

However, I wish here to concentrate on the essential similarity, which is that in both cases the virtual photon scatters incoherently from the constituents of the target. There are two salient features of the nuclear example which I want to stress:

(a) The onset of incoherence takes place for Q^2 less than the square of the mass of the constituent, and this is perfectly understandable since the nucleus is a weakly bound system. Incoherence sets in when $Q^2 >> 1/L^2$, where L is the inter-nucleon spacing, $L \sim 1$ fm.

(b) The quanta (pions, ρ mesons) which bind the nucleons to form the nucleus also give the nucleon structure (form factors) which causes the simple scaling behavior to be violated (and in the nuclear case, it happens that it is violated before it can begin, since by the time Q^2 is large enough for the individual nucleons to scatter incoherently, the electromagnetic current is already probing within their structure clouds).

We may suppose that a similar picture applies to the electron-nucleon scattering case if the nucleon is considered a composite system. Since we actually do see scaling occur in this case (Bjorken scaling) the constituents of the nucleon, if not actually point-like, must be much smaller than the nucleons themselves. The fact that the onset of scaling occurs at such small values of Q^2 suggests that the constituents of the nucleon may be effectively relatively light and weakly bound ($\gtrsim$ few hundreds of MeV).

The notion of weak binding of light quarks ($M_Q \sim 300$ MeV) to form the nucleon is in accord with analyses of baryon spectra and transition amplitudes which are generally computed with considerable success on the basis of a non-relativistic quark model. It also underlies the quark light-cone algebra and sum rules. The basic problem of why we don't "see" free, individual quarks or partons of the nucleon persists in this approach and I have nothing to add to the resolution of this problem.

As we now increase Q^2 to larger values, the electromagnetic current probes for internal structure of these constituents. There is the possibility that none will be found and the Bjorken scaling behavior is exact. In this "revolutionary" case we will have reached the ultimate constituents or the innermost layer of particle structure in nature and there will be no higher mass scale separating us from the light cone. Alternatively, pursuing the atomic, nuclear, and nucleon analogies one more round, the constituents of the nucleon may themselves have structure, and deviations from scaling will be ovserved when Q^2 and ν grow to values that excite their internal dynamics and probe their gluon cloud structure. However the very fact that we have found[6] scaling to occur to a good ($\approx \pm 15\%$) approximation in the region $1.5 < Q^2 < 10\ \mathrm{GeV}^2$ and $2 < \nu < 20$ GeV means that we have evidently not yet seen the form factor of the constituent, nor have the gluons that bind them and give them structure been produced as was the case for pions in Fig. 2. <u>These facts can be accounted for by asserting that the gluons are very heavy, and their mass defines a scale of new physics</u>.

In light-cone language, this picture corresponds to successive hierarchies of masses separating us from the light cone. Approximate scaling laws will be valid whenever there is an interval between adjacent mass or binding energy scales E_i and E_{i+1} such that

$$E_i \ll Q^2, \quad \sqrt{s} \ll E_{i+1} .$$

Scaling plateaus are observed in such preasymptotic regions.

In contrast, in the field theory and parton models with superconvergent behavior, scaling emerges from the formalism because there are no masses larger than the nucleon's, $M_p \approx 1$ GeV. In the deep inelastic Bjorken region the electromagnetic current has already seen through the structure cloud "dressing" the partons and is scattering from the point-like bare quanta or partons themselves. In these models the constituent form factor is a constant in the scaling region. Corrections to the scaling behavior and to the constancy of $F_c(Q^2)$ are proportional to $\approx M_p^2/Q^2$ and are negligible in the Bjorken limit.

In renormalizable theories, with spin degrees of freedom but with no momentum cut-offs, and therefore without superconvergent behavior when treated with an order-by-order iterative perturbation expansion, scaling is violated by logarithmic powers $\ln(Q^2/M^2)$ for $Q^2/M^2 >> 1$.

In fact it has recently been found[9] that the requirement of Bjorken scaling behavior is a very powerful restriction on possible forms of local quantum field theories when coupled with the renormalization group techniques originally introduced by Gell-Mann and Low and Stückelberg and Petermann.[10] The starting point of such investigations is Wilson's operator product expansion.[11] Deep inelastic scattering cannot be studied directly using renormalization group techniques - which are valid only at deep Euclidean momenta, if indeed anywhere, and not on the physical proton mass shell. However Wilson's operator product expansion allows one to relate moment integrals of structure functions to terms in the operator product expansion whose q^2-dependence is determined by the short distance singularities which are calculable from renormalization group techniques. Using these techniques one can determine classes of theories meeting the requirement of so-called asymptotic freedom[9] - i.e., the requirement that the strong interactions "turn off," or scale away, for large space-like momenta as required for establishing Bjorken scaling up to calculable logarithmic corrections. Only non-Abelian gauge theories have the property of so-called asymptotic freedom. Ordinary old-fashioned Yukawa-type theories fail this test.

This result is very exciting in view of the prominence of such theories in recent efforts to unify weak and electromagnetic - and perhaps strong - interactions. I for one have not yet understood all the subtleties raised by the infrared divergences in these theories but it appears that the requirement of a scaling asymptotic behavior, free of power law violations, constitutes severe constraints on quantum field theory models of strong interactions.

It is also of importance that logarithmic deviations are predicted fron exact scaling behavior. Also the approach to asymptotic behavior is not according to a power law, but only with logarithmically vanishing correction terms.[12] So if we are in the asymptotic region we must see such deviations - or else some powerful notions of quantum field theory must be reexamined and modified. Alternatively, if we are preasymptotic, more salient deviations from scaling behavior like new thresholds should appear.

Very simply then, the question is whether the presently observed scaling represents the asymptotic probing of point-like nucleon constituents or whether it represents a preasymptotic behavior in which one has not yet begun to see the structure of the constituent. And if we are asymptotic can we observe the approach to asymptotic behavior required by field theory?

At this time there is no definite evidence of the failure of scaling as Professor Bloom made clear in his talk.[6] But it is important to ask what room is there within present experimental limits for scaling to fail and for "new physics" to appear.

Consider for example a bound state model of a nucleon as discussed earlier: light, weakly bound constituents with a charge structure

$$F_c(q^2) \sim \left(1 - Q^2/M_G^2\right) \quad \text{for } M_p^2 << Q^2 << M_G^2 \tag{1}$$

where M_G is an "effective" gluon mass. One expects intuitively that such parton structure would alter the parton model results, and other results obtained assuming point-like constituents, by replacing point-like vertices by form factors $F_c(Q^2)$; viz.

$$\nu W_2(\nu, Q^2) \cong \mathscr{F}_2(\omega) \left(1-2\frac{Q^2}{M_G^2}\right) \tag{2}$$

for $M_p^2 \lesssim Q^2 << M_G^2$, where $\omega \equiv 2M_p\nu/Q^2$ and the factor 2 enters with the square of (1). This conjecture can be justified in simple Bethe-Salpeter models of the nucleon using the ladder approximation.[7]

What limits can we now put on possible values of M_G or the parton size? Alternatively what limits can be put on the appearance of Wilson's anomalous dimensions as evidence of scale breaking? Such dimensions introduce a Q^2 variation $\sim (M^2/Q^2)^{dn}$ into the moment integrals of the scaling functions as derived from Wilson's operator product expansions

$$B_n = \int_{1+M^2/Q^2}^{\infty} \frac{d\omega'}{(\omega')^{2n+2}} \left(\nu W_2(\omega', Q^2)\right) \tag{3}$$

Bloom[6] discussed the B_n for $n = -\frac{1}{2}$ to $n = 3$ in terms of the Bloom-Gilman scaling variable $\omega' \equiv \omega + M^2/Q^2 = \frac{W^2}{Q^2} + 1$. In his analysis Bloom terminated the integral in practice at an upper limit of $\omega' = 5$. He also used a value for the longitudinal to transverse cross section ratio that is constant: $R = .168$. This is consistent with the data, though not required by it, as analyzed in Riordan's[13] MIT Ph.D. thesis. Choice of the scaling variable ω' in (3) allowed the average effect of the resonances to be included in the moment integrals as suggested by duality. On the other hand the entire question of the role and importance of the resonance contributions is an ambiguity in this approach. Moreover there is need for obtaining experimental data in the resonance mass region above $Q^2 = 6\ \mathrm{GeV}^2$. With these caveats as to choice of scaling variable ω', the value of R, and the magnitude of the resonance contribution, Bloom found a suggestion of possible anomalous dimensions only from the higher n moments that put perilously large weights on the resonance region. But he found no evidence of parton size up to masses $M_G \gtrsim 12$ GeV.

On the other hand looking at the νW_2 directly as extracted from a mesh of existing data points in the two variables ν and ω, Riordan in his thesis[13] made a scaling study independent of assumptions about R. His published results are preliminary as he emphasizes since he has yet to complete an extensive study of systematic uncertainties which, as also emphasized by Bloom, can have a significant effect on the ratio R. Confining his analysis to hadronic masses W > 2.5 GeV above the resonance region Riordan found the results as shown in Fig. 3. The slight fall off of νW_2 with increasing Q^2 can be fit with a parton "size" in the range

$$M_G \sim 8\ \mathrm{GeV}$$

according to (2). In terms of the Bloom-Gilman variable on the other hand fits can be achieved without requiring any scale-breaking effects and so the above number could reflect nothing more than the choosing of an inoperative scaling variable.

How can we decide whether the apparent trend in the data should be attributed to the wrong scaling variable, ω instead of ω', or to parton size - if indeed the trend survives further analysis of systematic uncertainties, of the ratio R, and of higher Q^2 measurements in the resonance region?

In terms of ω' we have by Taylor expanding

$$\mathscr{F}_2(\omega') = \mathscr{F}_2(\omega + M^2/Q^2) = \mathscr{F}_2(\omega) + (M^2/Q^2)\,\mathscr{F}_2'(\omega)$$

and since $\mathscr{F}_2'(\omega) > 0$ for $\omega < 4$ we find that $\mathscr{F}_2(\omega')$ decreases as Q^2 increases, approaching scaling behavior in ω for large Q^2. Moreover since $\mathscr{F}_2'(\omega) = 0$ for $\omega > 4$ in this region scaling should be accurate for all Q^2. In contrast in terms of finite parton size the deviations from scaling[14] are <u>independent</u> of ω and <u>increase</u> with Q^2. Hopefully the crucial data for larger ω and Q^2 values will be available before long, from experiments now in progress at SLAC and, with muon beams, at NAL.

If experiment confirms that we are in the asymptotic, and not the preasymptotic region, it will be of crucial interest to gauge theories with the property of asymptotic freedom to observe the predicted logarithmic deviations from the scaling law as well as the logarithmic approach to scaling behavior.[9] Logarithmic approach of the ratio R for σ_L/σ_T to its asymptotic value should also be found[15] though this behavior is not in evidence yet. So the issue of asymptotic behavior, scaling, and what it may have to do with field theory are open and challenging.

III. Elastic Form Factors, the Time-Like Region, and Neutrino Processes

We turn next to the behavior of the elastic electromagnetic form factor of the proton at high Q^2 for a hint of the scale of "new physics." No general asymptotic theorems exist for elastic form factors and thus any interpretation in terms of possible constituent structure relies on specific theoretical models. The experimental facts are summarized in Fig. 4 which contains all data for the magnetic form factor of the proton $G_M(Q^2)$ plotted relative to a dipole form $(1 + Q^2/0.71\ \mathrm{GeV}^2)^{-2}$. A scaling relation is assumed to hold between the electric and magnetic form factors in Fig. 4, i.e., $G_M(Q^2) = 2.79\ G_E(Q^2)$, but the large Q^2 data are very insensitive to this assumption as the electric scattering is relatively very small. The dipole form has per se no fundamental theoretical significance. Furthermore the exact nature of the fall-off and the quantitative behavior of G_M for large Q^2 cannot be specified accurately or uniquely due to the limited data for $Q^2 \gtrsim 10\ \text{GeV}^2$. Fits to this data over the entire experimental range can be achieved by introducing complicated analytic forms;[16] however, if we use simple pole models, a large mass parameter, $\sim 5 - 10$ GeV, has to be introduced. As emphasized by Massam and Zichichi[17] a fit based on the vector dominance model, including the effects of the ρ, ω, and ϕ propagators, as well as their vector-dominated nucleon form factors, must be modified by introducing a heavy vector meson of mass $M_V = 7.7 \pm 1.1$ GeV to give the overall electromagnetic form factor a more rapid fall-off with increasing Q^2. Alternatively, a modification of the dipole formula in Fig. 4 by a multiplicative factor $\left(1 - Q^2/M_G^2\right)$ fits the data for $Q^2 > 5\ \text{GeV}^2$ for $M_G \sim 10$ GeV. Finally, if one makes a 3-parameter fit to G_M with the trial form

$$G_M = \frac{1}{\left(1 + \frac{Q^2}{M_1^2}\right)\left(1 + \frac{Q^2}{M_2^2}\right)\left(1 + \frac{Q^2}{M_3^2}\right)} ,$$

it is possible to find a good χ^2 over the entire range[18] of measured Q^2 in terms of two masses, M_1, $M_2 \sim 1 \pm 0.3$ GeV and with one large mass $M_3 \gtrsim 5$ GeV.

Independent of a specific theoretical interpretation the appearance of a large mass $M_G \sim 10$ GeV suggests the possibility of a new scale of large masses or short distances on which qualitatively new behavior may occur.

In addition to deviations from scaling as in Eq. (2), the most striking experimental consequence of speculations about possible parton size is for the behavior of the total cross section for electron-positron annihilation into hadrons in the single photon approximation. For $M_p^2 \ll s \ll M_G^2$ in the annihilation channel $s \equiv q^2 > 0$

$$\sigma_{e^+e^- \to \gamma \to X}(s) \propto \frac{1}{s} \left(1 + 2 \frac{s}{M_G^2}\right) \tag{4}$$

where the correction factor is just the root mean square radius approximation to the square of the constituents' form factors. To leading order in s/M_G^2 the rise in (4) <u>above</u> the point-like behavior has the same slope as the decrease below scaling behavior in the scattering region.[7] Physically the correction due to the constituents' form factor is introduced because the production time of the constituents, $\sim \sqrt{\frac{1}{s}}$, is not short compared with their interval of free particle propagation before they rescatter to form the final hadrons, i.e., $\sim \frac{1}{M_G} \ll \sqrt{\frac{1}{s}}$. Also, if the gluons have the same quantum numbers as the photon, i.e., vector gluons with unitary octet indices (perhaps due to SU_3 breaking), then the correction in (4) may grow to a resonance form $\sim 1/(1 - s/\mathcal{M}^2)^2$. Thus a sizable increase in the annihilation cross sections would be observed as $s \to \mathcal{M}^2$ while at the same time the corrections to scaling for the scattering experiments remain much smaller. The actual position of the resonance is however unknown since M_G, as already commented, is an "effective" mass in terms of coupling strengths and particle masses; therefore, we cannot identify $\mathcal{M}^2$ with M_G^2 defined by the effective range expansion in (4). Whether or not this phenomenon lies behind the apparent steep rise of the CEA total annihilation cross sections[2] for $e\bar{e} \to$ hadrons for $s \sim 16$ - 25 GeV^2, Fig. 5, remains to be seen.

Gauge theories which satisfy the conditions of asymptotic freedom as described earlier are found to lead asymptotically to an energy dependence of the total annihilation cross section characteristic of point-like particles - i.e., the $\frac{1}{s}$ in (4). This asymptotic behavior does not exhibit the logarithmic deviation that was found in the deep inelastic scattering from the scaling law. However Appelquist and Georgi[19] have shown that such gauge theories predict that this cross section approaches its asymptotic behavior logarithmically and from above - i.e.,

$$\sigma = \sigma_{\text{point}}\left(1 + \frac{c}{\ln s/M^2} + \ldots\right).$$

The model dependent constant c is positive and, for example, $c = +\,2/9$ for a triplet of red, white, and blue quarks. This is in clear conflict with the existing data at the presently studied energies.

In the very near future there should be considerably more evidence bearing on the question of scaling, both for space-like and time-like values of q^2. One qualitative feature is suggested by the data available at this moment: deviations from scaling in the space-like scattering region of $-q^2 \lesssim 10$ GeV^2, indeed if present,[6, 13] seem significantly less pronounced than the apparent enhancements above point-like for the time-like annihilation region[2] when $q^2 \sim 16$ - 25 GeV^2. If this feature is verified by future experiments, it can be accommodated within a model of finite size constituents if we assume that there is a resonant enhancement modifying (4) by $\left(1 + 2s/M_G^2\right) \to \left(\frac{1}{1 - s/\mathcal{M}^2}\right)^2$, as described earlier, with $\mathcal{M} \sim 8$ GeV. Additional data should indicate whether or not such an explanation is tenable. Alternatively we may appeal to the production of charmed, or colored, states by electromagnetic pair production with thresholds in the CEA energy region as accounting for the observed rise.

If such charmed constituents are largely absent from the nucleon's wave function we can also account for the much smoother behavior of the deep inelastic scattering structure functions with respect to possible scaling deviations. This is consistent with a remarkably simple picture of the proton structure emerging from the neutrino as well as the electron scattering data,[5] according to which the proton is built of the three valence quarks plus quark pairs confined to large ω or small x values only.

We are presently at a critical juncture in our understanding of these cross sections and there is a high premium on confirming the scaling behavior, deviations therefrom and the approach thereto, with precision.

The view that scaling is a <u>preasymptotic</u> phenomenon has further experimental implications.

The same correction factor in (4) also modifies the scaling behavior predicted for one-body inclusive cross sections $e + \bar{e} \to h + X$, as well as the massive lepton pair production $p + p(n) \to \mu\bar{\mu} + X$ (or $e\bar{e} + X$) for finite ratio Q^2/s, where Q^2 is the invariant squared mass of the lepton pair and s the total reaction $(\text{energy})^2$. An important aspect of this process is that the scaling prediction $d\sigma/dQ^2 \sim (1/Q^4)\mathcal{F}(Q^2/s)$ is based on a parton model analysis. It cannot be derived from the more formal application of light-cone techniques without also introducing dynamical parton model assumptions about the contributions of the leading singularities.[20]

It looms to me as of great importance to test this scaling prediction. It is a direct test of the applicability of the parton model idea that one can treat the proton as made of point-like constituents that behave as free during the impulse of a hard, sudden kick. Measurements at different energies s and the same finite ratio Q^2/s are required. As to the magnitude of the cross section, this requires the application of model dependent ideas - in particular of the anti-parton content of the proton wave function; and, as discussed by Professor Franzinetti,[5] the recent results from the CERN and NAL neutrino experiments measure a ratio of $\bar{\nu}$ to ν inelastic cross sections that is close to 1/3 indicating that the anti-parton content is small and confined to small values of $x < 1/4$.

Turning to the neutrino experiments at NAL and CERN, these can establish whether scaling behavior applies for the weak as well as for the electromagnetic currents and can set new limits on possible scaling deviations. They carry us into new kinematic regions of higher energy values, ν or W^2, and perhaps across the conjectured production thresholds for gluons. Whereas SLAC is limited to $W^2 < 40\ \mathrm{GeV}^2$, for neutrinos and muons at NAL energy transfers as large as several hundred GeV can now be achieved and hence hadronic final states of very high masses

$$W^2 = M^2 + 2M\nu - Q^2 \gtrsim 400\ \mathrm{GeV}^2$$

will be produced. Hence we can greatly extend scaling information; and we can produce massive gluons of masses $M_G \sim 10$ GeV if they indeed exist. Moreover the point-like nature of the weak interaction means that the counting rate for probing to larger Q^2 values will not be inhibited by a decreasing factor of $1/Q^4$ arising from the photon propagator; in fact the mean momentum transfer is given roughly by $\langle Q^2 \rangle \sim 2/3M\nu$ in the scaling region.

It has already been established, Figs. 6 and 7, in the first round of neutrino experiments at NAL, up to $\langle Q^2 \rangle \sim 15$ GeV^2 and a maximum neutrino energy of $E_\nu \sim 150$ GeV that scaling is consistent with the data up to cut-off masses of $\gtrsim 10$ GeV whether such masses are attributable to heavy gluons or the weak interaction bosons. With greater precision and more events at high energies one may expect to observe from both ν and μ inelastic scattering the salient qualitative feature of a nonscaling bump when crossing whatever gluon production thresholds there are.

The locations of such thresholds will be of course sensational if they are a reality. Predicting their location is sensitive to dynamical details relating effective gluon masses to real ones. Indeed following this picture literally leads to the deepening mystery: where are the light constituents themselves? Why are they not observed? Are there real gluons?

In this connection, it is interesting to consider the alternative hypothesis to the picture I have used in my discussion. Suppose that the constituents and the gluons are <u>both</u> very massive, say $\gtrsim 10$ GeV. In this case one might not expect to see s^{-1} scaling behavior in e^+e^- annihilation until $s \gg 4M^2_{\text{constituent}}$, and the range of time-like momenta presently under experimental investigation might be too small to reveal any easily understood scaling behavior. In contrast, the effective mass of the constituent inside the nucleon could be small as a result of the strong binding forces. If this were the case and the proton behaves as a weakly bound system we would see in the inelastic scattering the early onset of incoherence and "preasymptotic" scaling behavior as I have discussed. Turning once again to nuclear matter for a guide we find from the results of Stanfield[8] and the analysis of Moniz[21] that the nuclear forces cause a qualitative shift in the effective nucleon mass decreasing it by as much as 30%, as shown in Fig. 2. Due to the considerably stronger forces binding such massive constituents within the nucleon there could well be an even greater difference between effective bound constituent masses and free masses. In this way we might hope to accommodate "preasymptotic" scaling for inelastic scattering measurements at precociously small values of space-like q^2, without at the same time having simple point-like behavior for the annihilation cross section at comparably small values of time-like q^2.

The locations of any such preasymptotic thresholds are also important for determining when one saturates sum rules derived from local current algebra relations, such as the Adler sum rule for neutrino-nucleon scattering:[22]

$$\int_{\nu_t}^{\infty} d\nu \left[W_2^{\bar{\nu}p}(\nu, Q^2) - W_2^{\nu p}(\nu, Q^2) \right] = 2 \qquad (5)$$

Sum rules such as (5) are mathematical abstractions until we say when they are saturated. In a constituent model such as we have been describing we find according to (2) that

$$\int_{\nu_t}^{\infty} d\nu \left[W_2^{\bar{\nu}p}(\nu,\ Q^2) - W_2^{\nu p}(\nu,\ Q^2) \right] = 2\left(1 - 2\frac{Q^2}{M_G^2}\right) \text{ for } M_p^2 << Q^2 << M_G^2$$

if we neglect in W_2 the production of massive gluons which occurs with a threshold $\nu_{in} \cong M_G^2/2M_p$. However we expect that the remainder, or $+4Q^2/M_G^2$, which saturates the Adler sum rule comes from gluon production above the gluon threshold ν. Simple Bethe-Salpeter bound state models as well as perturbation calculations confirm this result,[7] which relies only on the local equal time algebra and the assumption that no subtractions are required for the odd amplitude under crossing, in accord with standard Regge asymptotic arguments.

IV. Probing Neutral Currents and PCAC

Exploring the weak lepton currents further, the $q^2 - W^2$ plane has been literally opened to scientific exploration during the last year as we have learned at this conference,[5] and it is a matter of collecting data and accumulating statistics - and hopefully discovering new particles before this landscape as viewed by weak currents takes form. Qualitatively as probed thus far the parton or light-cone scaling picture is confirmed without surprises. The only surprise is that it works so well! The most exciting and crucial discovery of neutral currents reported[23] from Gargamelle and NAL restores some welcome balance in a year when theorists have invented literally dozens of Higgs scalars, heavy leptons, and heavy vector neutral and charged bosons that are the quanta of the weak currents.

What else happens as we sail far out in the $Q^2 - W^2$ regions for the weak interactions requires that we speculate very heavily and dangerously. That, of course, is much of what a theorist usually does, but I will stay near to the shores of the $q^2 - W^2$ plane with hopes of also staying in closer contact with reality.

First, let's follow down the q^2 axis of Fig. 1. Neutral current contributions will in general interfere with the electrodynamic interaction of e-p scattering. For example, for V and A type non-parity conserving interactions two effects may appear:

(a) Deviations from the Rosenbluth form following from a scattering pattern in the cross channel (t-channel) center of mass system that is proportional to

$$\propto \left[a + b \cos \phi_t + c \cos^2 \phi_t \right]$$

with $b \neq 0$ indicating parity violation.

(b) Polarization effects for scattering of polarized electron beams. For example, any dependence of electron-proton scattering on the longitudinal polarization of the electrons would be evidence of parity violation.[24]

Probably it will be necessary to push far beyond the present lepton scattering ranges since the relative importance of the weak and electromagnetic amplitudes is measured by

$$R \left\{ \left[\frac{\text{weak neutral current}}{\text{QED}} \right] (Q^2) \right\} \sim \frac{GQ^2}{4\pi\alpha} \; f \left\{ \frac{F_{weak}(Q^2)}{F_{elm}(Q^2)} \right\}$$

and

$$R(30 \text{ GeV}^2) \sim 3 \times 10^{-3} \; f \left\{ \frac{F_{weak}(30)}{F_{elm}(30)} \right\}$$

where f is the ratio of neutral to charged current amplitudes (< ½) and the bracketed ratio is the ratio of the form factors of the vector currents.

Although $F_{elm}(30) \equiv G_M(30) = \frac{2.79}{(1 + 30/.71)^2} \sim 1.5 \times 10^{-3}$ there is no reasonable expectation that F_{weak} will be two or more orders of magnitude larger. However the naive expectation of R growing as Q^2 points to higher energies, characteristically $Q^2 \sim 1000\ \mathrm{GeV}^2$ for 5-10% anticipated effects.

A more immediate speculation concerns the probing with weak currents along the W^2 axis near $Q^2 \sim 0$. This permits the study of the partially conserved axial current hypothesis (PCAC) to extend away from its regions of established successes near $Q^2 = 0$ and $W^2 \sim M^2$ for the various soft pion theorems, in particular the Goldberger-Treiman relation between weak pion decay and strong pion-nucleon interaction constant which is the genesis of PCAC.[25] Additional soft pion successes are the Adler-Weisberger sum rule, the Adler consistency theorem, and the Callen-Treiman relation for $K_{\ell 3}$ decay. At large W^2, but $Q^2 \to 0$, it is also possible to study PCAC for hard pions as first pointed out long ago (1964) by Adler[26] who noted that for forward neutrino scattering from nucleons the lepton matrix element is proportional to the momentum transfer q_μ up to corrections due to finite lepton mass. Hence what is measured is the divergence of the weak hadronic current, viz.

$$
\begin{aligned}
q^\mu \langle ps|J_\mu|(n)\rangle &\propto \langle ps|\frac{\partial J_\mu}{\partial x_\mu}|(n)\rangle \\
&\xrightarrow[\text{cvc}]{} \langle ps|\frac{\partial A_\mu}{\partial x_\mu}|(n)\rangle \\
&\xrightarrow[\text{(PCAC)}]{} \frac{F_\pi \mu_\pi^2}{\mu_\pi^2 - q^2} \langle ps|j_\pi|(n)\rangle
\end{aligned}
$$

where j_π is the source of the pion field. In this way Adler derived a relation between $\left(\frac{d\sigma(E_\nu)}{d\Omega_\ell}\right)_{0^\circ}$, the forward inelastic neutrino differential cross section

$$\text{and} \qquad \int_{(M+\mu_\pi)^2}^{M^2+2ME_\nu} dW^2 \sigma_{tot}^{\pi^\pm p}(W^2) \left\{ \text{kinematic factors} \right\} .$$

where $\sigma_{tot}^{\pi^\pm p}(W^2)$ is the total pion-nucleon cross section for a total invariant energy W. A study of this relation will help clarify just what is PCAC by testing the underlying assumption which identifies the divergence of the weak axial current with the pion amplitude in a kinematic region heretofore unexplored when $W^2 > 6M_p^2$ is above the resonance region. At issue is whether this pion pole dominance assumption is true for all matrix elements or just the soft pion ones for hadronic interactions.

The practical question as to whether this represents a measurable process has been studied in detail by Giles and by Preparata and de Vincenzi[27] who have analyzed corrections to the Adler result coming from finite muon mass and for slightly non-forward scattering as observed by a detector with a finite acceptance solid angle in the reaction $\nu + N \rightarrow \mu + \ldots\ldots$ The kinematic range dominated by the PCAC contribution and the estimated counting rates for practically designed experiments were discussed, and in particular Giles analyzed the possibility of distinguishing between possible corrections to or modifications of PCAC and kinematic effects. Though difficult in practice the Adler proposal of forward inelastic neutrino scattering offers a unique opportunity for testing PCAC.

In addition to their basic importance to fundamental theory and the hope of unifying weak and electromagnetic interactions the gauge theories provide specific models for searching for deviations from QED.

We have mentioned the possible interference of neutral currents in the interpretation of elastic e-p scattering. The muon (g-2) value is one of the most sensitive probes of new surprises at high momenta (masses) or at very small distances and constitutes a constraint on possible models. The muon (g - 2) calculation based on pure QED through order α^3 agrees beautifully with precise measurements to date:[28]

$$\left(\frac{g-2}{2}\right)_{\mu}^{exp} = (116{,}616 \pm 31) \times 10^{-8}$$

$$\left(\frac{g-2}{2}\right)_{\mu}^{th} = (116{,}581.4 \pm 1.4) \times 10^{-8}$$

$$(\mathrm{exp} - \mathrm{QEDth}) = (35 \pm 31) \times 10^{-8}$$

To the theoretical expression we must also add at this level of precision the hadronic correction to the photon propagator which contributes

$$\left(\frac{g-2}{2}\right)^{had.\ vp} \cong \frac{\alpha^2}{9\pi^2} M_{\mu}^2 \int_0^{\infty} \frac{ds}{s^2} \left[\frac{\sigma^{tot}_{e\bar{e}\to had}(s)}{4\pi\ \alpha^2/3s}\right] =$$

$$= (6.6 \pm 0.9) \times 10^{-8} \qquad (s < 4\ \mathrm{GeV}^2)^{29}$$

$$+ (\sim 0.5) \times 10^{-8} \qquad (\text{if } \sigma^{tot}_{e\bar{e}} \text{ grows as at CEA to } s \sim 100\ \mathrm{GeV}^2)$$

The agreement is thus to better than one standard deviation.

Future CERN experiments[30] hope to improve the experimental uncertainty by a factor $\sim$ 10 which brings us not only into the region of detecting quantitatively the hadronic vacuum polarization corrections to g - 2, but also brings us to the verge of restricting possible forms of gauge theories due to the weak current corrections.[31] Such corrections are generally $\lesssim 10^{-9}$ in Weinberg/Salam-type theories with heavy neutral vector bosons; but for Georgi-Glashow theories with heavy leptons rather than neutral vector bosons one finds upper bounds on the heavy lepton masses of $\sim$ 7 GeV with details depending on the Higgs mass (> ½ GeV by K decay) and the $W^{\pm}$ mass (20-53 GeV). Evidently we are already at the region where precision QED experiments limit the maneuverability for possible forms of gauge theories; and with higher precision this will improve. Direct measurements in production experiments of $e^+e^- \to$ (heavy currents) and of pp $\to$ (heavy vectors) + hadrons, which leads via the parton annihilation mechanism to the scaling prediction mentioned earlier, will also bring welcome and concrete challenges to these exciting theoretical constructs for unifying weak and QED theories. Various "reasonable" estimates already are pushing Z^0 masses up to $\sim$ 13 Gev.[32]

This selective peering into unknown regions of lepton interactions has omitted the whole field of what we are now learning about the secondary hadrons emerging from lepton induced processes with changing Q^2, much of which has been discussed during this conference.

What does the decade ahead hold in store? What will the Photon, Electron, and Neutrino Conference of 1983 be talking about? On the theoretical side we can look forward to a unification of weak and electromagnetic currents into a unified theory which must at least tell us why Nature has created the muon as well as the electron. Experimentally we can hope to roam the distant reaches of the $Q^2 - W^2$ plane to energies of 1000 GeV^2 and larger with colliding electron-proton beams, designs for which are already under study.[33] After adding one or more decades in Fig. 1

to the scale being probed we'll have added opportunities for many thresholds of "new physics" to appear, a lot of prescience will be turned into science,[34] and it may be a lot clearer whether or not we're actually "seeing" the light cone or whether we should prefer the world view of Anaxagoras to that of Democritus.[35]

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34. According to Leonardo da Vinci in Codex Trivulzio: "Science is the observation of things possible, whether present or past; prescience is the knowledge of things which may come to pass."

35. I.e., can matter be indefinitely subdivided into seeds each as complex as the whole, as claimed by Anaxagoras, or do we see the ultimate "atoms" of Democritus?

FIGURE CAPTIONS

1. Regions of the $q^2 - W^2$ plane that have been explored or are being explored experimentally. Note that for pictorial purposes the total annihilation cross section is represented by a vertical line (CEA 1973) at $W^2 = 0$ whereas in fact the measurement includes all W^2 in the kinematically allowed range: $\mu_\pi^2 \lesssim W^2 \lesssim \left(\sqrt{q^2} - \mu_\pi\right)^2$. For references to the experimental measurements of two-body and multi-body structure functions see Refs. (2), (5), and (6).

2. Inelastic electron scattering from carbon nuclei. The data and theoretical curves are taken from Ref. (8) The cross sections are plotted as a function of the scattered electron energy for given scattering angle (θ) and incident electron energy (ε_i). M^* denotes the effective mass of the nucleon used in calculating the quasi-elastic (incoherent) contribution to the theoretical curves. The momentum transfer at the peak of the cross section is given as indicated.

3. νW_2^p vs. Q^2 for fixed ω taken from Riordan's thesis. See Ref. (13).

4. Ratio of the magnetic form factor of the proton to the dipole form, $\left[1 + Q^2/.71\right]^{-2}$, plotted vs. Q^2. Taken from Ref. (16).

5. Ratio of total annihilation cross sections to point-like cross sections vs. Q^2. See Ref. (2).

6. Scaling behavior of the total ν cross section [Cal Tech experiment at NAL; see Ref. (5)].

7. Scaling behavior of the total ν cross section [Harvard-Penn.-Wisconsin at NAL; see Ref. (5)].

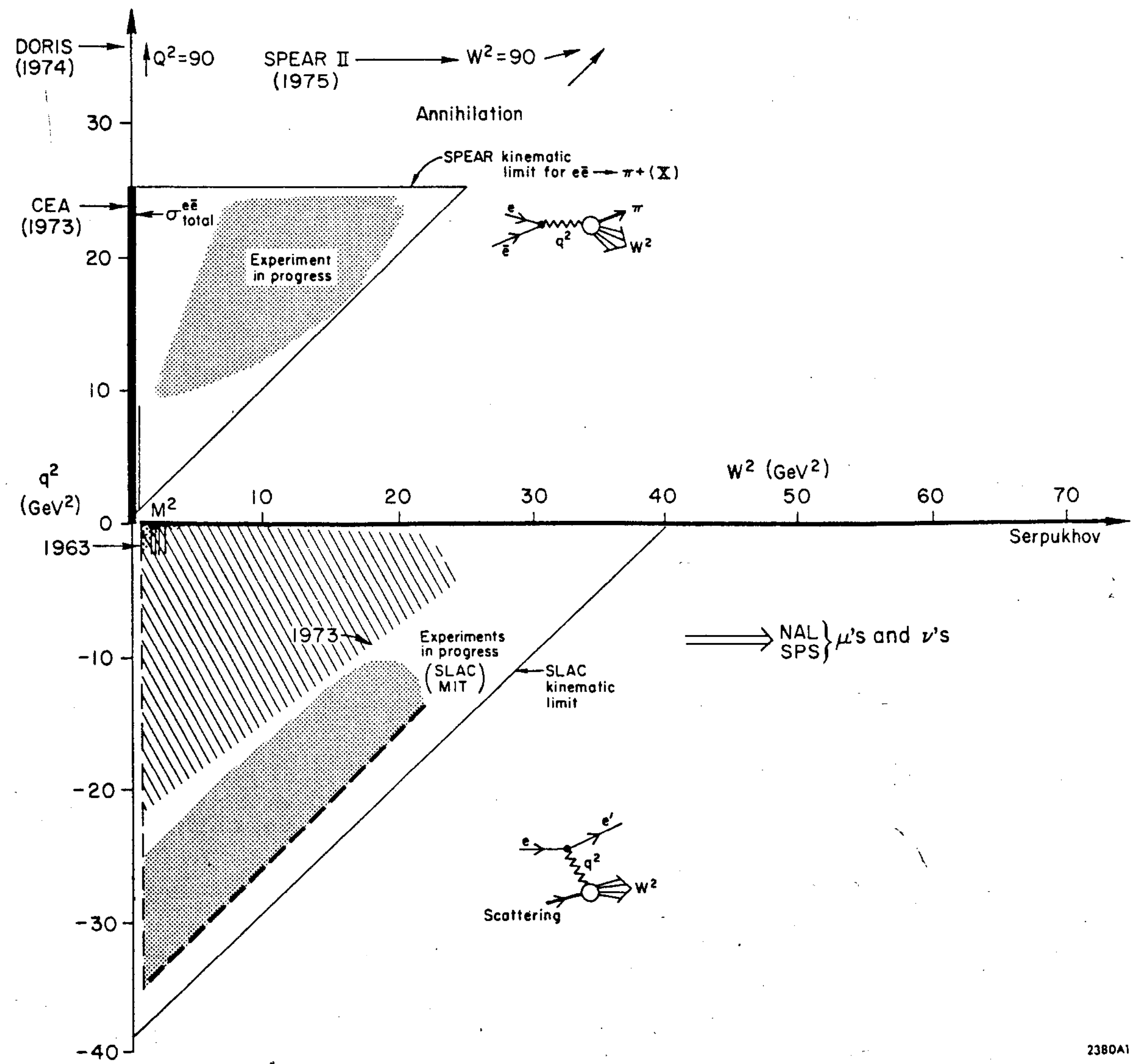

DORIS (1974)
Q^2=90
SPEAR II (1975)
W^2=90
Annihilation
SPEAR kinematic limit for $e\bar{e} \to \pi + (X)$
CEA (1973)
$\sigma^{e\bar{e}}_{total}$
Experiment in progress
q^2 (GeV^2)
W^2 (GeV^2)
M^2
1963
Serpukhov
1973
Experiments in progress (SLAC MIT)
SLAC kinematic limit
NAL SPS } μ's and ν's
Scattering
2380A1

Fig. 1

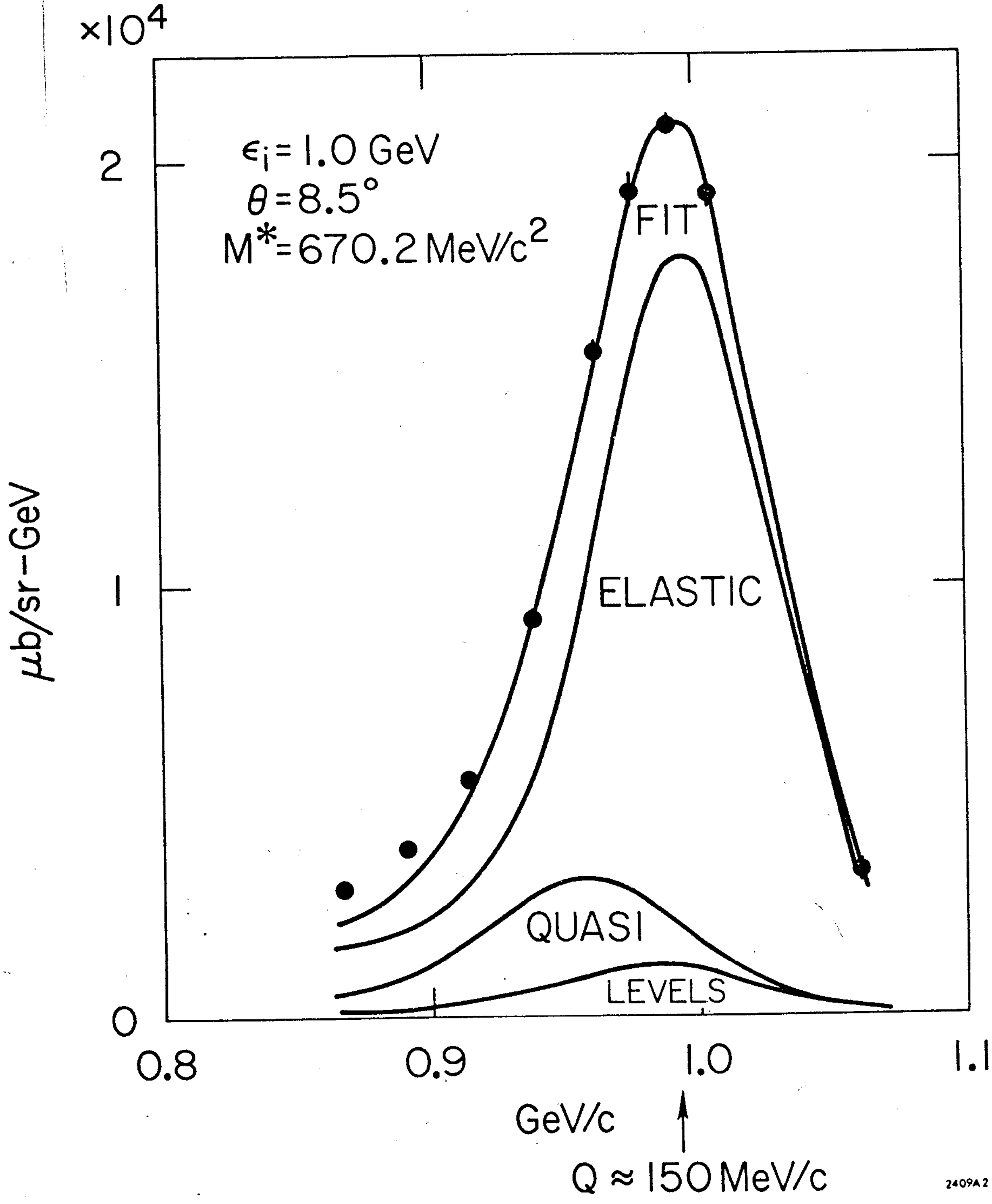

×10^4
ϵ_i = 1.0 GeV
θ = 8.5°
M* = 670.2 MeV/c²
2
1
0
FIT
ELASTIC
QUASI
LEVELS
μb/sr-GeV
0.8
0.9
1.0
1.1
GeV/c
Q ≈ 150 MeV/c
2409A2

Fig. 2a

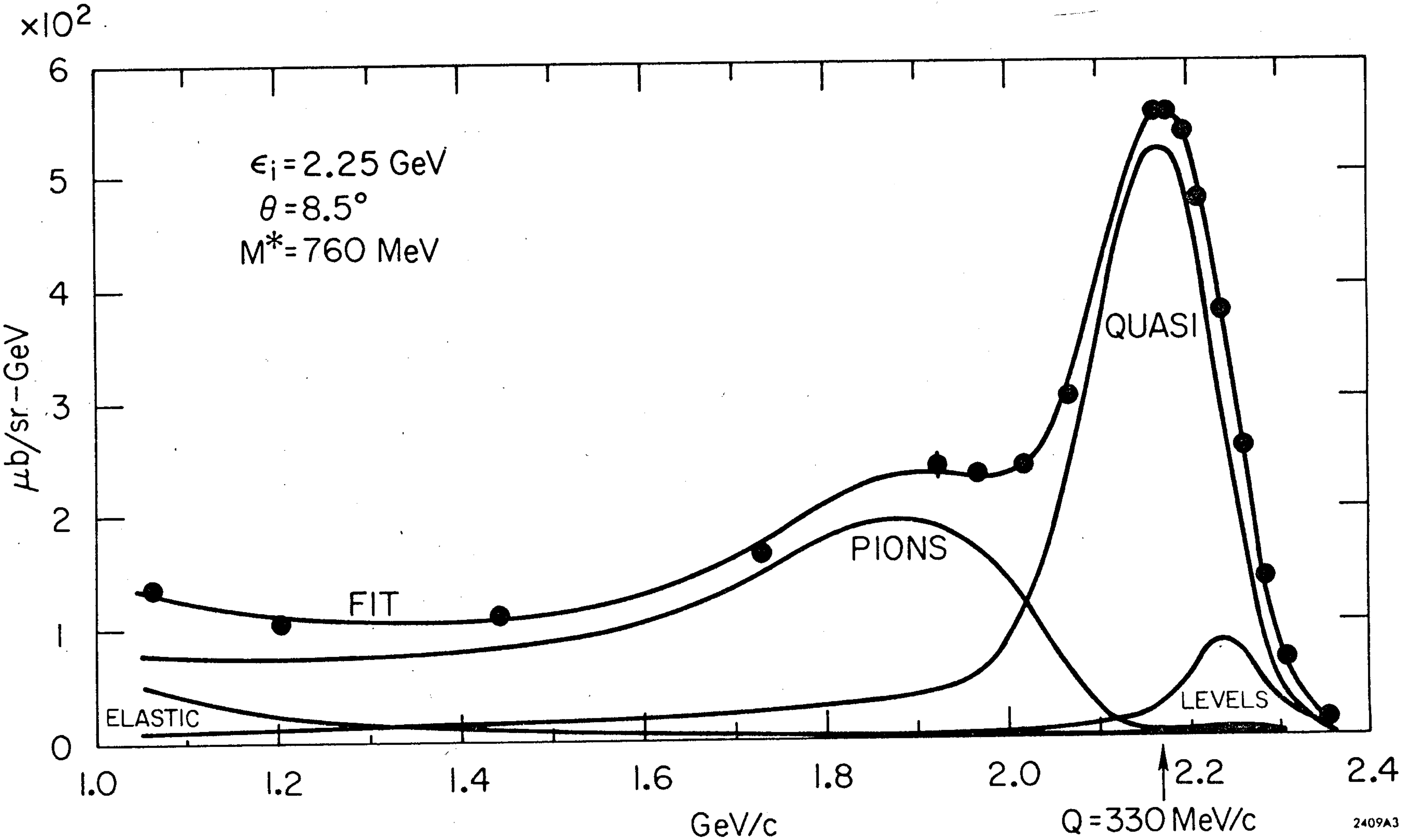

×10²
μb/sr-GeV
6
5
4
3
2
1
0
ε_i = 2.25 GeV
θ = 8.5°
M* = 760 MeV
QUASI
PIONS
FIT
ELASTIC
LEVELS
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
GeV/c
Q = 330 MeV/c
2409A3

Fig. 2b

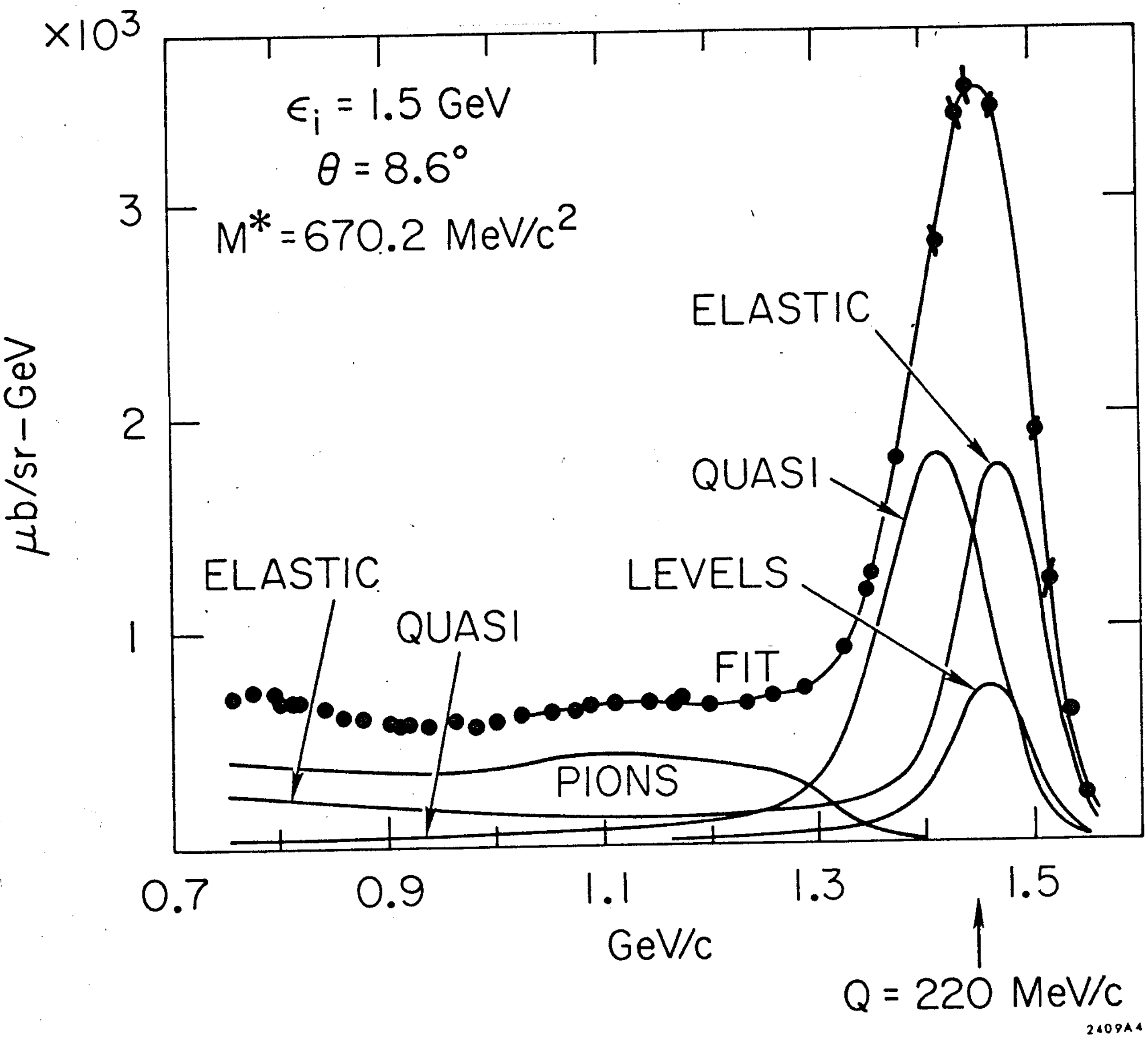

×10³
ϵ_i = 1.5 GeV
θ = 8.6°
M* = 670.2 MeV/c²
μb/sr – GeV
3
2
1
ELASTIC
QUASI
LEVELS
FIT
ELASTIC
QUASI
PIONS
0.7
0.9
1.1
1.3
1.5
GeV/c
Q = 220 MeV/c
2409A4

Fig. 2c

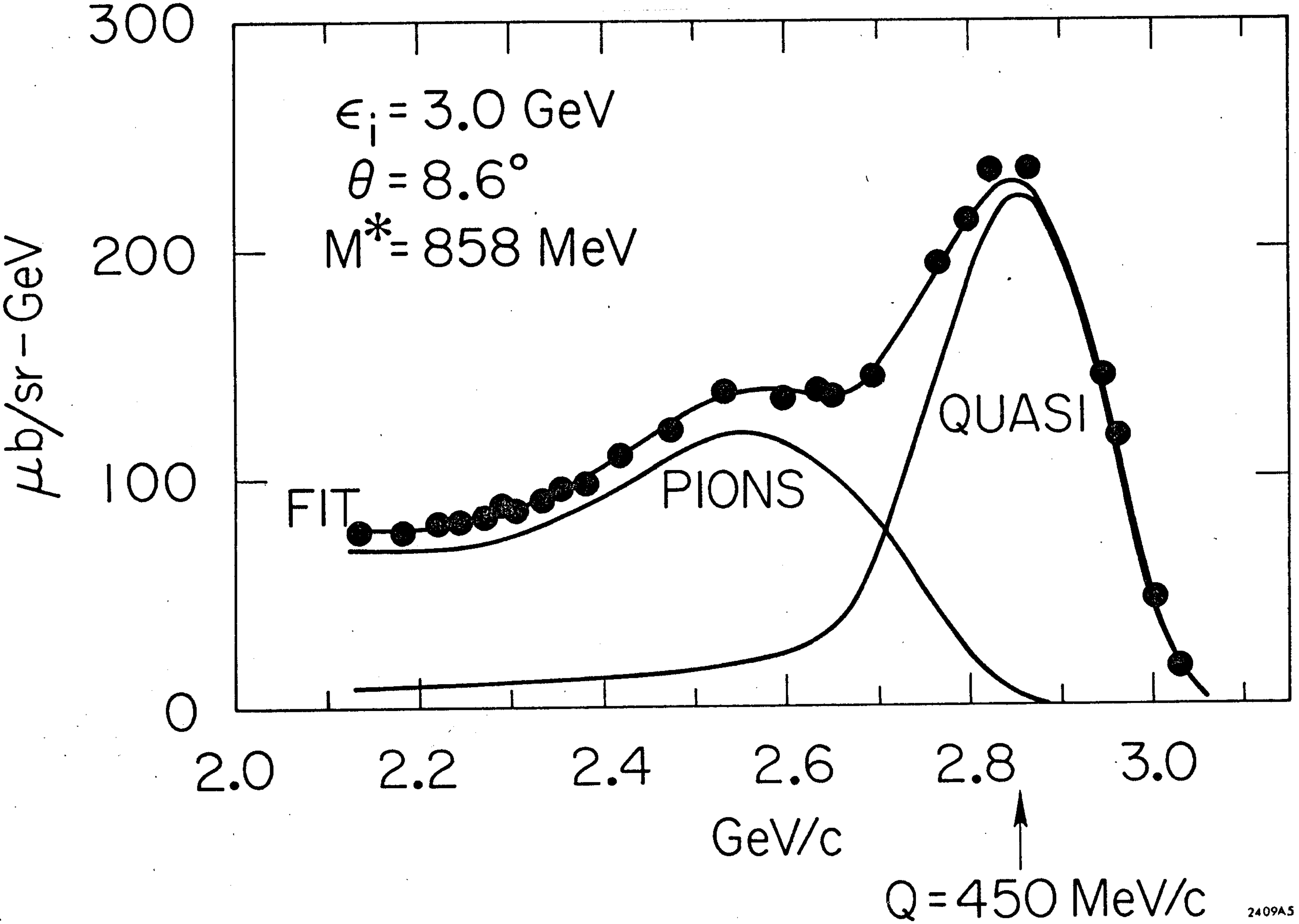

300
200
100
0
μb/sr – GeV
ϵi = 3.0 GeV
θ = 8.6°
M* = 858 MeV
FIT
PIONS
QUASI
2.0
2.2
2.4
2.6
2.8
3.0
GeV/c
Q = 450 MeV/c
2409A5

Fig. 2d

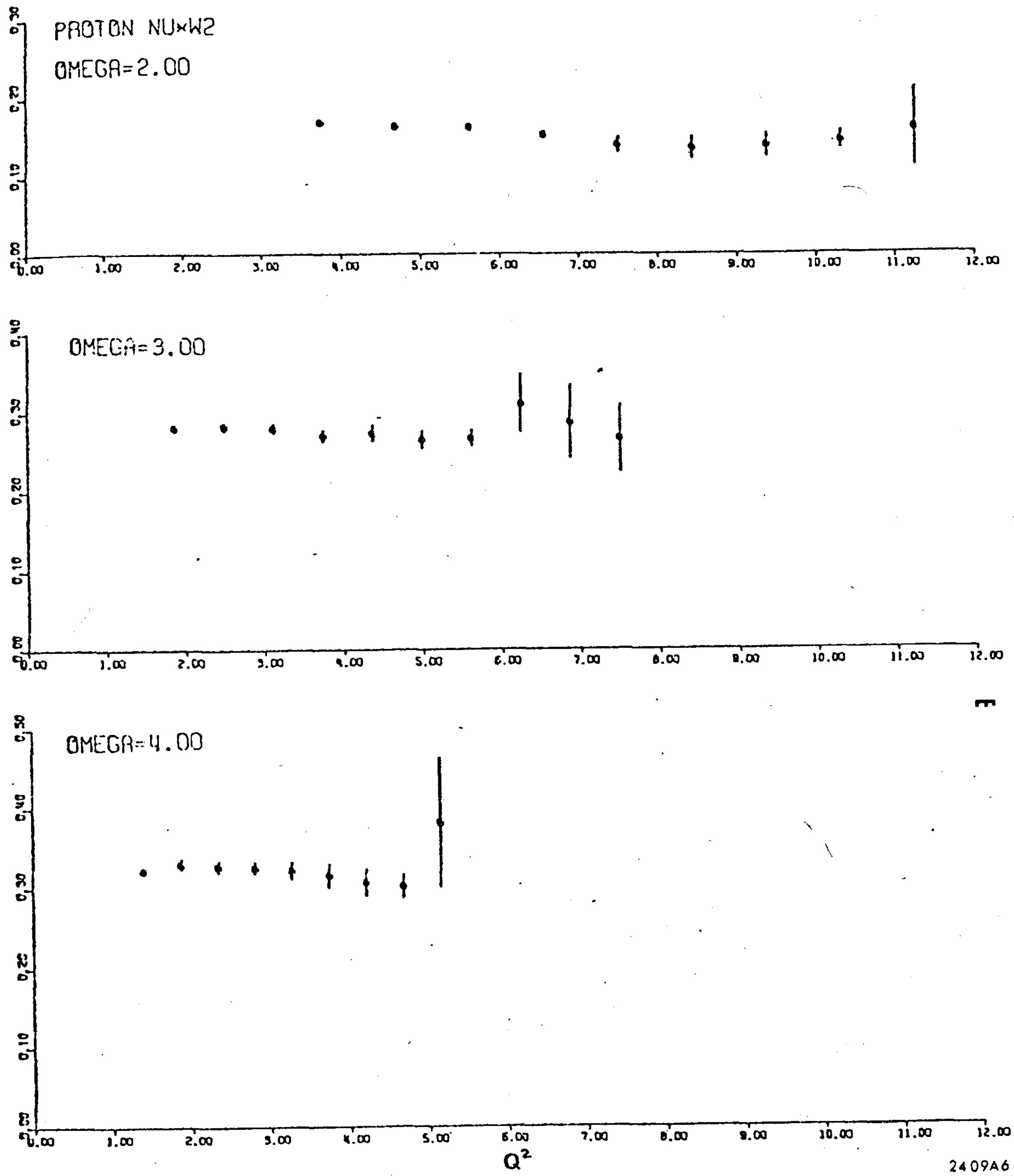


Fig. 3

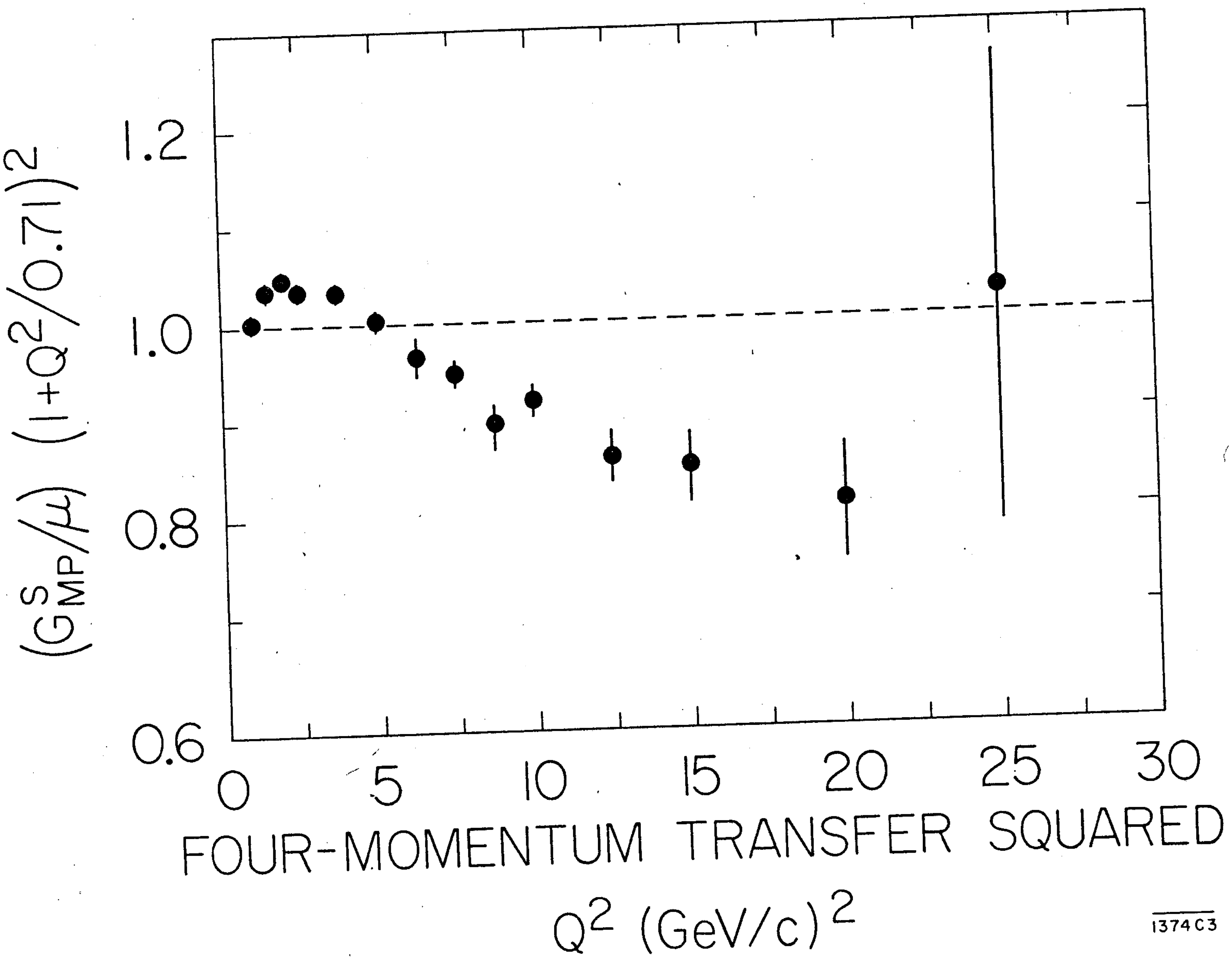
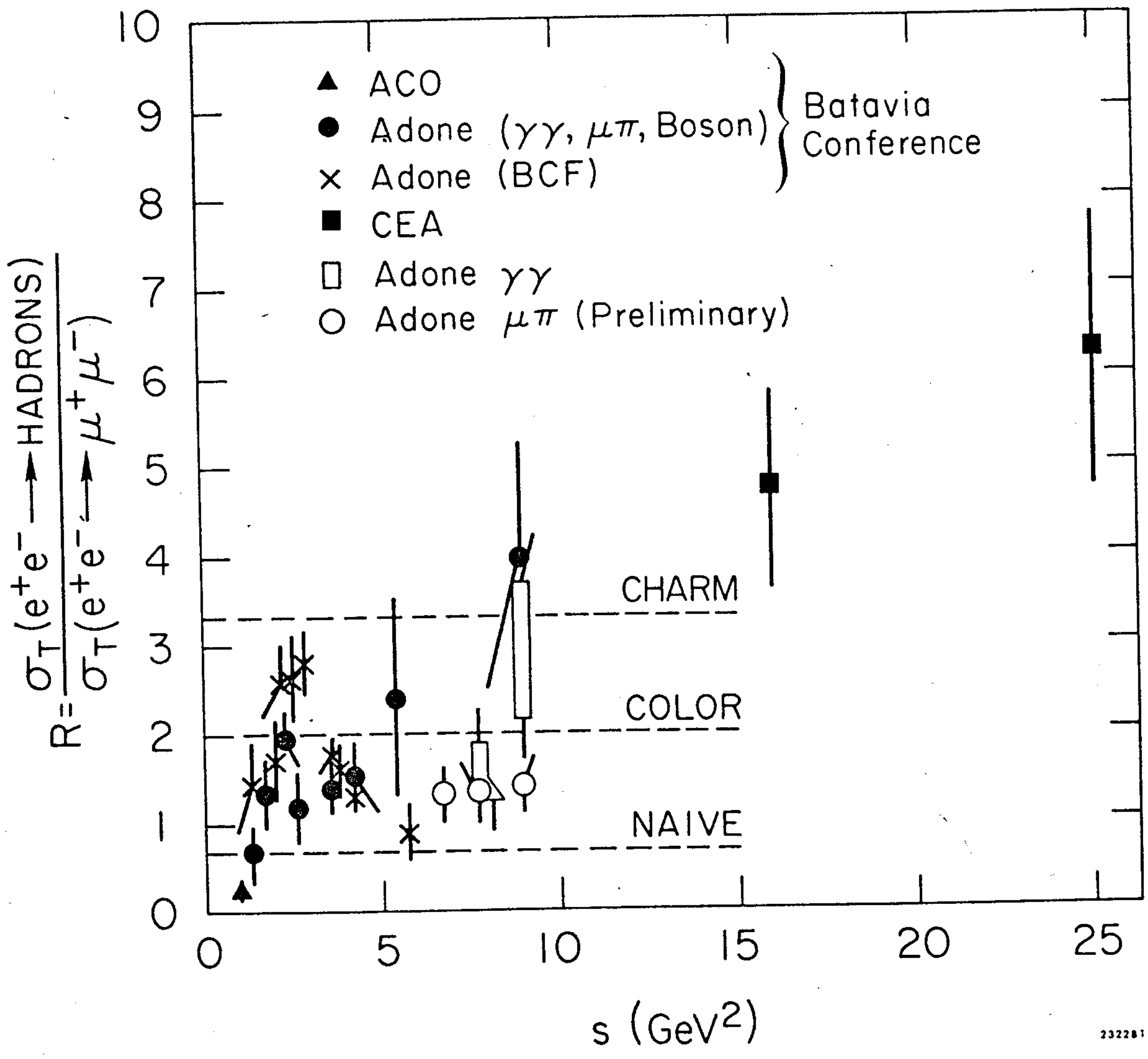

$(G^S_{MP}/\mu)\ (1+Q^2/0.71)^2$
1.2
1.0
0.8
0.6
0
5
10
15
20
25
30
FOUR-MOMENTUM TRANSFER SQUARED
Q^2 (GeV/c)^2
1374C3

Fig. 4



ACO
Adone ($\gamma\gamma$, $\mu\pi$, Boson)
Adone (BCF)
Batavia Conference
CEA
Adone $\gamma\gamma$
Adone $\mu\pi$ (Preliminary)
CHARM
COLOR
NAIVE
$R = \frac{\sigma_T(e^+e^- \rightarrow \text{HADRONS})}{\sigma_T(e^+e^- \rightarrow \mu^+\mu^-)}$
s (GeV^2)
232281

Fig. 5