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ELECTROMAGNETIC INTERACTIONS AT VERY HIGH ENERGY*

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It is easy for a theorist to talk about expectations for particle reactions at higher energies. He knows the answer: he will be wrong. Nevertheless, he is derelict in his duty if he doesn't try to guess. These days the word "prediction" is often meant to be the explanation of last year's experiments. We should strive for more, lest it be said that the science of high-energy physics is more backward than meteorology.

What can we expect at higher energies? In the realm of pure quantum electrodynamics, we have an essentially complete theory to tell us. Higher energies will allow extension of conventional QED tests[1] to shorter distances; in addition, the dominating role of μ-beams for proton machines will allow μ-trident production ($\mu^- + p \to \mu^+ + \mu^- + \mu^-$ + hadrons) to join scattering, pair-production, and bremsstrahlung as good electrodynamics tests. But the high-energy storage rings with their high center-of-mass energy will very likely provide the greatest progress in this field.

In processes directly involving hadrons, theory is not so reliable. A guide, useful from both the pragmatic side and from the point of view of theory per se, is the search for scaling-laws which suggest how to extrapolate to higher energies. The first part of this talk will deal with such scaling laws which have some basis from the experimental facts. This includes two-body (and quasi two-body) photoproduction and the deep inelastic electroproduction. The second part of the talk will consider scaling behavior based more on theoretical conjecture than on facts. Such scaling laws include the predictions for single-particle spectra a la Feynman and Yang, and conjectures regarding hadron yields in colliding-beam experiments.

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Finally, we will mention miscellaneous electromagnetic topics which at higher energies are simply new.

I. SCALING LAWS WHICH ARE FAIRLY GOOD

A. Two-Body and Quasi-Two-Body Photoproduction

Excellent data on forward and backward two-body photoproduction now exists, and it has been repeatedly reviewed.[2] Despite the rather complicated Regge-pole analyses, the facts show a remarkable simplicity and regularity:

(1) For forward photoproduction in the channels πN, $\pi\Delta$, ηN, $K\Sigma$, $K\Lambda$, the cross section behaves as

$$\frac{d\sigma}{dt} \approx \frac{1}{s^2} f(t) \tag{1}$$

which is in fact a scaling law. Furthermore, for $-t \gg 1\ \mathrm{GeV}^2$, $f(t) \propto e^{3t}$, while for smaller t there exist channel-dependent bumps and wiggles.

(2) For backward photoproduction

$$\frac{d\sigma}{du} \approx \frac{1}{s^3} f(u) \tag{2}$$

The exponent in the s-dependence is just the number of quarks exchanged, in the simplest exchange-model of the process.

(3) For photoproduction of ρ, ω, ϕ (A2, ρ', ... ??) one expects

$$\frac{d\sigma}{dt} \approx f(t) \tag{3}$$

as the norm, with the possibility of slow shrinkage or expansion of the diffraction-peak an open question. At present the optical picture given by (3) suffices.

These statements, while very naive, I believe have as much predictive power as the existing models as a basis for estimating the cross sections.

B. Deep-Inelastic Electroproduction, Muoproduction, and Neutrino Production

At very high energies and virtual-photon masses, the electroproduction ($e^- + p \to e^- +$ hadrons) cross section[3] is largely determined by a single structure-function, now known as νW_2, which is a function of photon laboratory energy ν and its squared mass Q^2 (taken positive when spacelike). The second structure-function can be conveniently taken to be σ_S/σ_T, the ratio of longitudinal to transverse virtual photoabsorption cross sections. It turns out that only when E', the final electron energy, is much less than the initial energy, is the cross section sensitive to the magnitude of σ_S/σ_T. Similar statements hold for the neutrino processes, where one function $\nu\beta$ (or $\nu\widetilde{W}_2$) controls the major features, while the two others $(\sigma_{R,L}/\sigma_R+\sigma_L+2\sigma_S)$, shape the finer details of the muon distribution.[4]

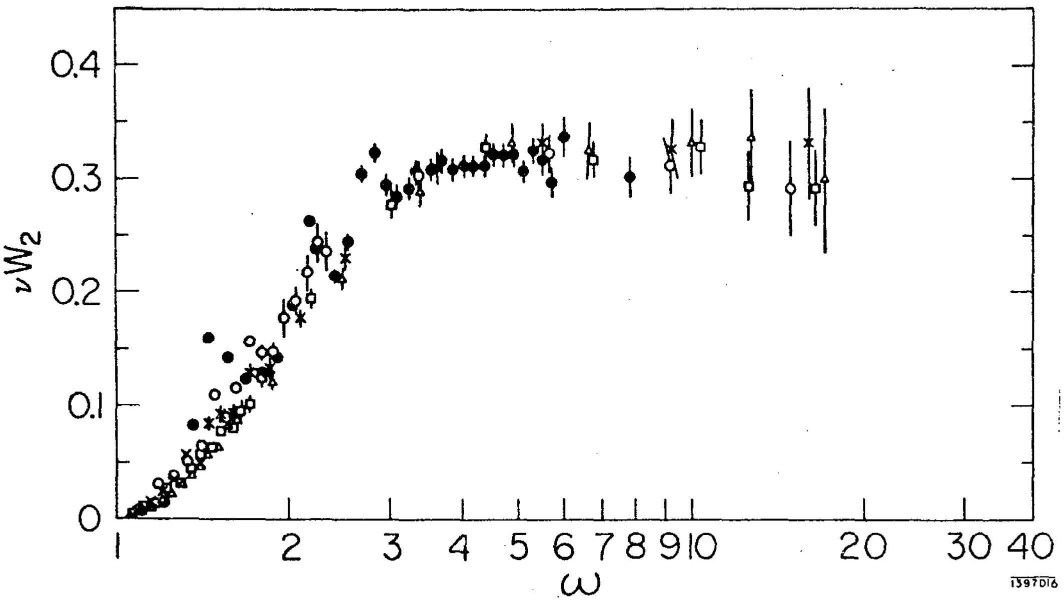
Experimentally, when Q^2 is greater than 1 GeV^2, νW_2 is approximately constant ($\approx .33$) over a large range of Q^2 and ν, and when the ratio ν/Q^2 becomes small it appears to follow a scaling law:

$$\nu W_2 = F\left(\frac{2M\nu}{Q^2}\right) \tag{4}$$

where F is shown in Fig. 1.

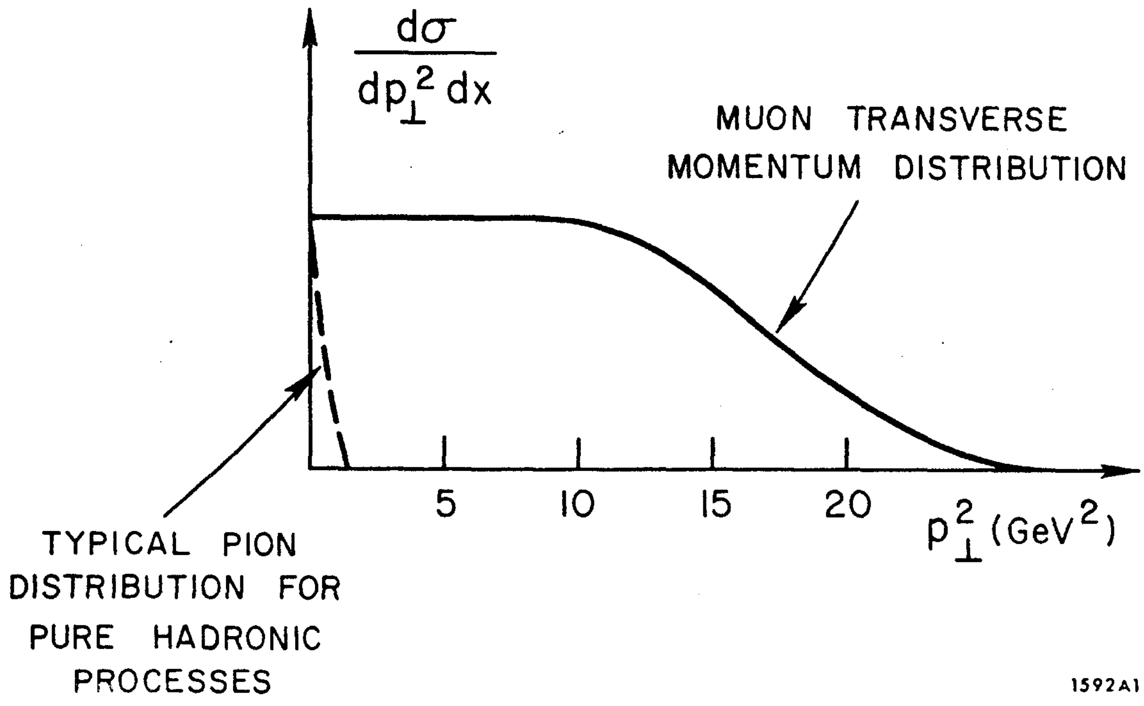
The theoretical basis for this scaling is tenuous at best; we can only be grateful that the data exhibits such simplicity. The other form factor, σ_S/σ_T, is measured to be $\approx 0.2 \pm .2$ in the range $M\nu/Q^2 \approx 1$-2 (near the peak) and with $Q^2 \sim 1$ to 4 GeV^2. More of this is in Taylor's talk.[5]

The most important implication of this result is the probable occurrence of large cross sections at high transverse momentum at high energies. The most spectacular case is in the neutrino processes. If we plot the expected



0.4
0.3
0.2
0.1
0
νW_2
1
2
3
4
5
6
7
8
9
10
20
30
40
ω
1397D16

Fig. 1



$\frac{d\sigma}{dp_\perp^2\,dx}$
MUON TRANSVERSE MOMENTUM DISTRIBUTION
5
10
15
20
$p_\perp^2$ (GeV^2)
TYPICAL PION DISTRIBUTION FOR PURE HADRONIC PROCESSES
1592A1

Fig. 2

$d\sigma/dp_\perp^2 dx$ (with $x = E_\mu/E_\nu$) versus $p_\perp^2$ for a 40 GeV muon emerging from a reaction initiated by an 80 GeV incident neutrino, we get Fig. 2.

This assumes that the muon distribution can be obtained from electroproduction via CVC plus some relatively harmless auxiliary guesses.[6] For electroproduction or muoproduction the dependence is $\sim p_\perp^{-4}$ (the square of the photon propagator), but, even so, as the energy goes up these leptons take an increasing share of signal from the backgrounds from more typical hadronic processes.

The dynamics underlying the scaling property of νW_2 is not clear. Those who like partons (i.e., the electron scatters incoherently from structureless constituents within the nucleon) anticipate differences when similar processes are compared. For example:

(a) $W_{2n} \neq W_{2p}$. A popular number[7,8] for the ratio W_{2n}/W_{2p} is ~ 0.8.

(b) $\sigma_{\nu n}^{tot} \neq \sigma_{\nu p}^{tot} \neq \sigma_{\bar{\nu} n}^{tot} \neq \sigma_{\bar{\nu} p}^{tot}$. Typically $\sigma_{\bar{\nu} N} < \sigma_{\nu N}$ with the estimates[6,8] of $\sigma_{\bar{\nu} N}^{tot}/\sigma_{\nu N}^{tot}$ running from 0.3 to $\lesssim 0.7$ (here N refers to nuclei).

(c) Polarization asymmetry[9] in electroproduction: $\sigma_P \neq \sigma_A$, where σ_P and σ_A refer to parallel or antiparallel configurations of electron and proton helicities. The asymmetry expected is of order 20% throughout the deep inelastic region.

(d) Perhaps $\nu W_2 \longrightarrow 0$ as $\nu/Q^2 \rightarrow \infty$ (Q^2 fixed).

Point (c) might be checked with muon beams from NAL which come naturally polarized. Point (d) may have to be settled with experiments at energies considerably higher than presently attainable at SLAC.

In contrast with parton enthusiasts, those who like a vector-dominant, diffractive picture[10,11] replace all the inequalities by equalities; in (d) $\nu W_2 \rightarrow$ constant $\neq 0$ as $\nu/Q^2 \rightarrow \infty$. Such a possibility is so dull that it is probably the right answer.

Before leaving all this, it is worth mentioning that because the empirical result for νW_2 is so simple, the electroproduction experiment provides evidence (but certainly not proof) against structure at the electron vertex or in the photon propagator. Assuming a typical cutoff of electron vertex $(1 + Q^2/\Lambda_e^2)^{-1}$, then a value of $\Lambda_e \sim 3$ GeV would change the effective νW_2 by a factor 2 at $Q^2 = 4$, ruining the simple scaling behavior. If scaling persists up to $Q^2 \sim 16$, the limit Λ_e becomes 6 GeV, well exceeding the present limit from colliding-beam experiments. To make such an argument we have to assume God is not malicious. In the long run, the storage rings will probably overtake easily such a limit, and provide a cleaner test as well.

II. CONJECTURED SCALING LAWS

A. Multibody Hadron Final States; Prologue

New concepts are needed in dealing with the complex multiparticle final states of very high energy. New tools are needed to supplement the Dalitz-plots and effective-mass plots which have been so useful in the past. So before discussing future experiments on multibody production, I will digress and speculate about future theories – theories along the lines of the s-channel optical, eikonal,[12] droplet,[13] parton,[14] or impact[15] pictures of high energy collisions. The basic point of view I want to give is illustrated by considering high-energy nucleus-nucleus collisions at, say, 10 GeV/nucleon in the c.m.s. There will be four stages in the collision-process.

(1) Before: The internal motion within the incoming nuclei is slowed by time-dilation and we may think of the incident particles as (pancake-shaped)

beams of free constituents, including the meson-cloud associated with the nuclear potential.

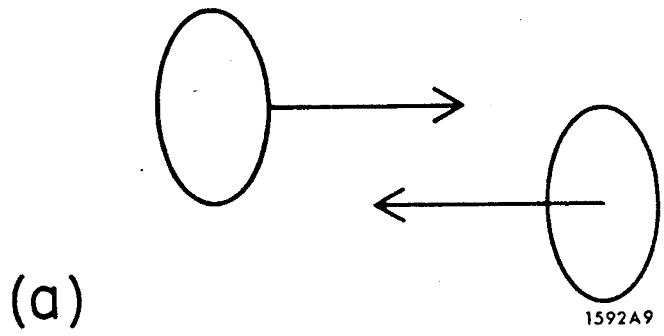


FIG. 3(a)

(2) <u>During</u>: The collision is instantaneous. Terrible things happen in the overlap region.

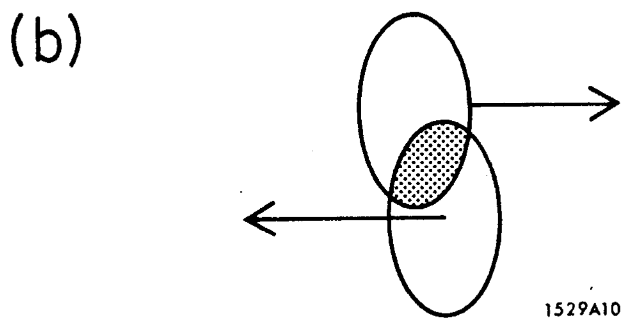


FIG. 3(b)

(3) Immediately after: At least 3 components emerge.

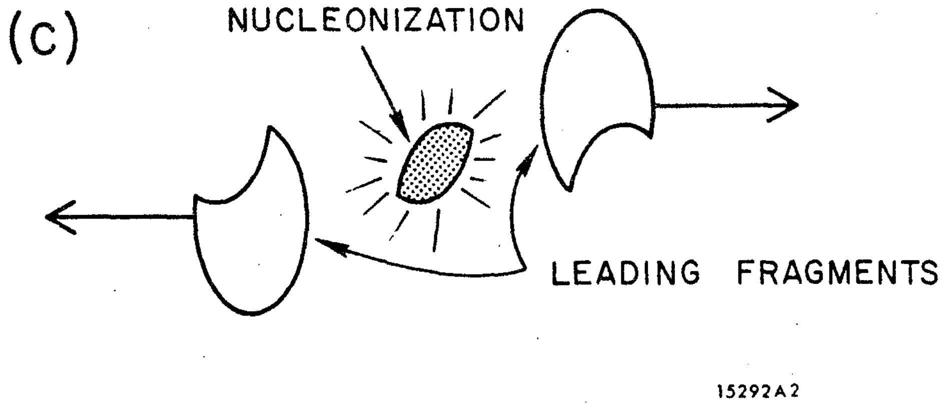


FIG. 3(c)

(4) Long afterward: Decay of the leading fragments into leading nucleons and nuclei.

While it is probably unwise to attempt a literal imitation of this dynamics to hadron-hadron collisions, it may be that there are features in common. For example, there will be leading particles (the products of leading fragments). I would propose that there are also some lessons to be learned:

(a) The intermediate state formed after the collision is not a pure resonance (unless the collision is very peripheral). No resonance will have the shape of a quarter-moon. The mass of the intermediate state, however, will be reasonably well-defined, being just a peculiarly-shaped chunk of nuclear matter. Lesson: It is likely that the properties of a group of final states, when a course-grained energy average is made, will represent the quarter-moon and may have more fundamental significance than the ultimate specific decay-channels.

(b) The impact parameter is determined by the fraction of nucleons in the group of leading particles, i.e., by the properties of secondary particles.

Likewise, the transverse-momenta of secondaries should be correlated relative to the collision-plane. This correlation again depends on impact parameter. Lesson: An effort should be made to try to define an impact-parameter and collision plane for individual hadron-hadron events.

Coarse-grained averaging of the data is necessary and desirable to study these kinds of properties. To figure out the right averages to take and the right distributions to construct may well require a close collaboration of theorist and experimentalist (so close that their names appear on the same paper), so that the differing perspectives and instincts of each can be synthesized.

As an example of a statistical function, consider correlations of the transverse momenta. Are they isotropic, or do they tend to lie along a line? To test, construct the following quadrupole tensor:

$$T_{ij} = \frac{1}{N} \sum_{k=1}^{N} \frac{\left(p_\perp^{(k)}\right)_i \left(p_\perp^{(k)}\right)_j}{\left(p_\perp^{(k)}\right)^2} - \frac{1}{2} \delta_{ij} \tag{5}$$

where N is the number of secondaries. For each event compute the eigenvalues t of T_{ij} and plot the distribution (Fig. 4):

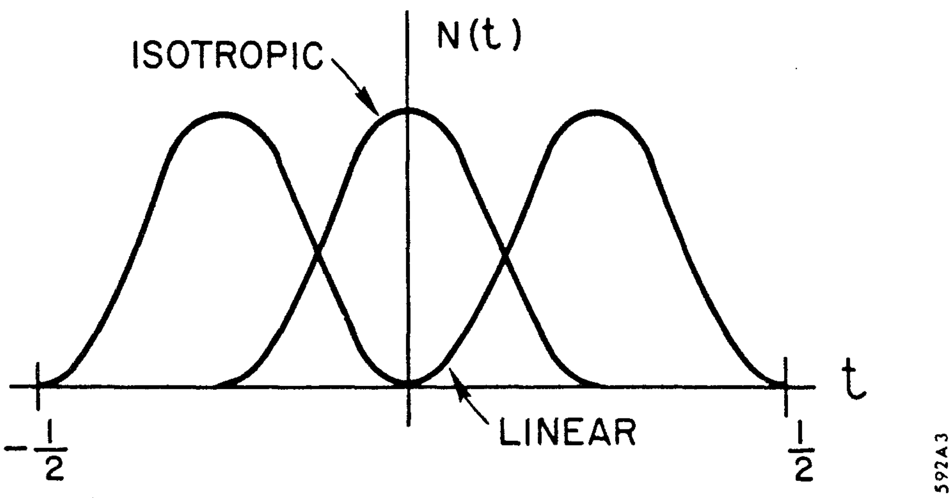


FIG. 4

This may or may not work. It is only intended as an example of what might be tried.

Most of the attention at present is devoted to single-particle spectra. The conjectures of Feynman[14] and Yang[16] provide a convenient framework for comparing experiment with theory. The proposal is that secondary distributions be analyzed in terms of the transverse-momentum $p_\perp$ and the longitudinal fraction $x = p_\parallel / E_0^*$, where $p_\parallel$ is the z-component of c.m.s. longitudinal momentum and E_0^* is the c.m.s. energy of the incident particles. There is predicted to be a limiting distribution in these variables as $E_0^* \longrightarrow \infty$. Empirically for pp or πp collisions the transverse momentum distribution of π's is roughly fitted by an exponential[17]

$$\frac{dN}{dp_\perp^2} \approx C\, e^{-ap_\perp} \tag{6}$$

This distribution is fairly universal and a tempting proposal is that

$$\frac{dN}{dp_\perp^2\, dx} = \frac{1}{x}\, f(p_\perp)\, g(x) \tag{7}$$

with importance of the 1/x emphasized by Feynman. For small (wee) x, replace x by $\sqrt{x^2 + \frac{m^2 + p_\perp^2}{E_0^{*2}}}$. Equation (7) is a scaling law which should have been explored experimentally years ago.

Some guesses for g(x) are shown in Fig. 5.

B. Multibody Final States in Photoproduction

With this digression into pure hadron physics, we return to photoproduction of multibody hadron states. For two-body processes, the photon acts very much like a massless ρ^0, which by the quark model behaves for many purposes like a π^0. Therefore, the secondary distributions from photoproduction should look

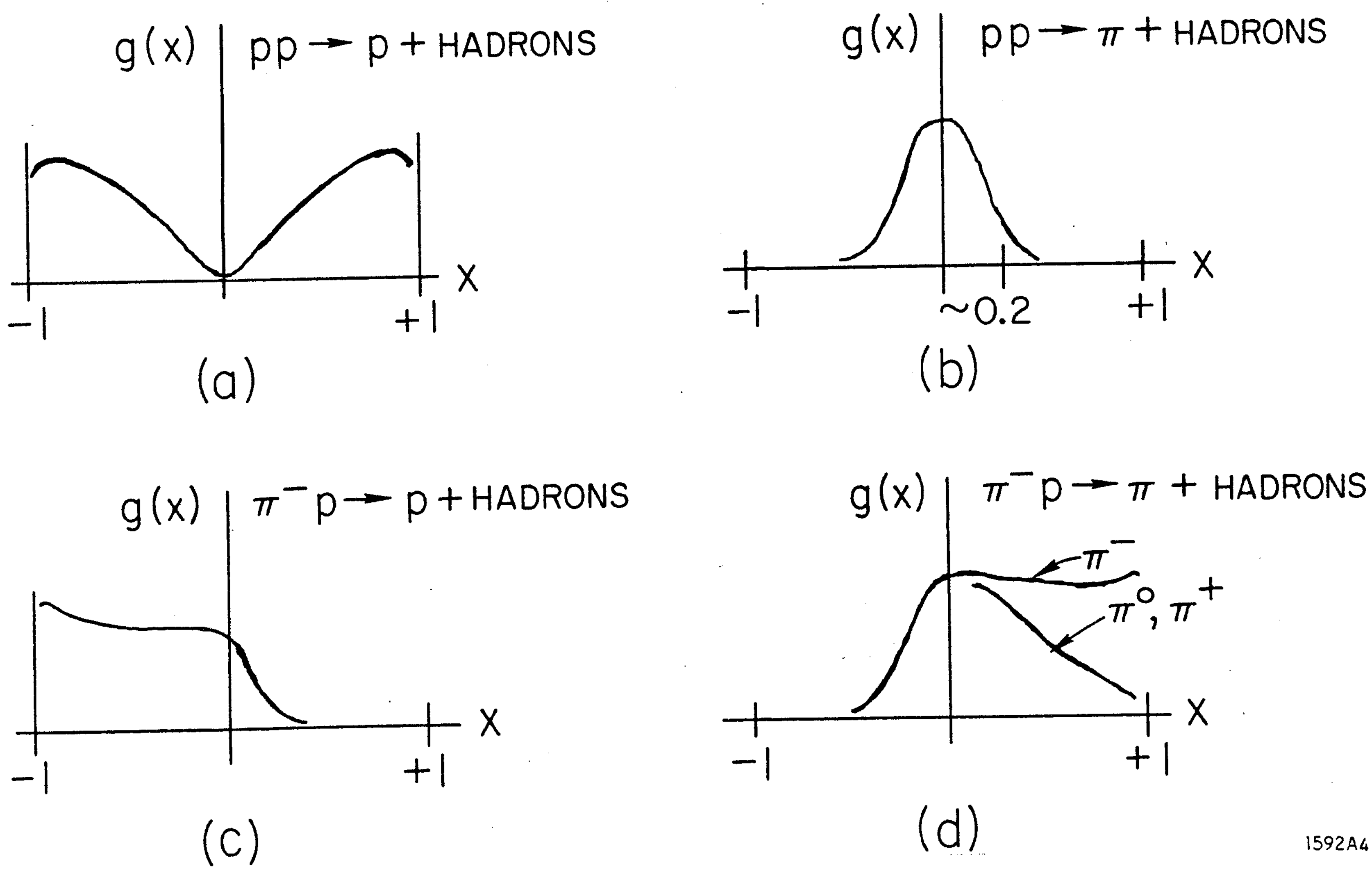

g(x)
pp → p + HADRONS
X
−1
+1
(a)
g(x)
pp → π + HADRONS
X
−1
~0.2
+1
(b)
g(x)
π⁻p → p + HADRONS
X
−1
+1
(c)
g(x)
π⁻p → π + HADRONS
π⁻
π°, π⁺
X
−1
+1
(d)
1592A4

Fig. 5

very much like those from π-p (not pp) collisions. There is one exception; the decay π's from ρ^0 photoproduction have no analogue in π-nucleon absorption and are an additional large contribution at small $p_\perp$. The SLAC beam survey data were understood reasonably well in these terms by Crossland.[18]

C. Multibody Final States in Electroproduction, Muoproduction, and Neutrinoproduction

At present there is much interest in exploring the nature of the hadron distributions in deep-inelastic electro-, muo-, and neutrinoproduction. Suppose the virtual photon is indeed being absorbed in the nucleon by nucleon constituents, or partons. Then if these partons carry baryon-number as well as charge, one might anticipate a relatively large fraction of the secondary nucleons to have large laboratory momentum.

On the other hand, if the vector-dominance or diffraction-picture of the process[10] is correct, the target nucleon plays a passive role. In this latter case, the target fragments with negative x [in the c.m.s. of virtual photon and target proton] might be expected to satisfy Yang's limiting fragmentation hypothesis[16] and have the same distribution as for real-photon, pion, or proton-induced processes. However, in the diffraction-picture the distribution of fast particles of positive x may well change as Q^2 becomes large. The argument for this is that the coherence-length λ (the inverse of the minimum momentum transfer to the target) is $\sim 2\nu/(Q^2 + M^{*2})$, where M^* is the mass of the forward-moving state existing after the impact. Thus, while for real photons the coherence-length decreases rapidly for increasing M^*, this isn't the case for the highly virtual photon. We conjecture that this implies the mean mass $\langle M^* \rangle$ to be $\sim\sqrt{Q^2}$ at high Q^2. After the impact, the heavy M^* object decays. If it were to decay on the average into a fixed number of secondaries, the momentum per secondary (in the M* rest frame) would increase proportional to M*. That probably means high transverse momentum $p_\perp$ as well. But hadrons rarely possess high $p_\perp$, so a perhaps more likely alternative is that the momentum per secondary (in the M* rest frame) remains small, with the consequences

(a) The number n_s of forward ($x > 0$) secondaries (mainly pions) is $\alpha \sqrt{Q^2}$. We conjecture

$$n_s(\nu, Q^2) \lesssim \sqrt{\frac{Q^2+m^2}{m^2}} \; n_s(\nu, 0) \tag{8}$$

with $m \sim m_\rho$.

(b) The mean $p_\perp$ of the secondaries (relative to the momentum axis $\underset{\sim}{q}$ of the virtual photon) is ~ 0.3-0.4 GeV just as in ordinary hadron processes. Most models will agree with this conjecture. Cheng and Wu, on the basis of behavior in pure QED, disagree.[19]

(c) The mean longitudinal fraction x of the secondaries decreases as Q^2 increases because the total momentum is shared among more particles.

This is all highly conjectural. However, we urge that the experiments (this includes the neutrino experiments) should be analyzed in terms of Q^2, ν, $\underset{\sim}{p}_\perp^{(k)}$, and $x^{(k)}$ (as defined in the c.m.s. of virtual photon and target nucleon). It is also important to emphasize that measuring hadron distributions in the deep inelastic region isn't going to be productive unless the results can be compared with the corresponding ones in photoproduction and π-induced processes. As yet there is far too little data on those!!

D. Colliding Beams and Scaling Laws

1. Total Cross Sections

Theoretical speculations on the total cross section[20] give $\sigma_{tot} \sim s^{-n}$, with $n \sim 1 - 3$.

The arguments are:

n = 1: dimensional analysis, partons, divergent Schwinger term.

n = 2: diffraction electroproduction[21] (maybe).

n = 3: ρ, ω, ϕ-dominance[22] (strictly[23] $\sigma_{tot} < s^{-2} (\log s)^{-1}$).

2. Single-Particle Distributions

A statistical model[24] predicts the momentum distribution of secondaries (mainly π's) to be similar to the transverse-momentum distribution in ordinary collisions. The mean energy of a pion (in the c.m.s.) is thus ~350 MeV and consequently the multiplicity is proportional to $\sqrt{s}$ (and rapidly grows to ~10-15 charged particles at the CEA energy). The single-particle distribution of π's, aside from an overall factor of $\sqrt{s}$, should be independent of s. In contrast to this, the parton model of Drell, Levy, and Yan,[25] in which the secondary-antiproton distribution satisfies a scaling law similar to electroproduction (c.f. Eq. (4) and Fig. 6), gives

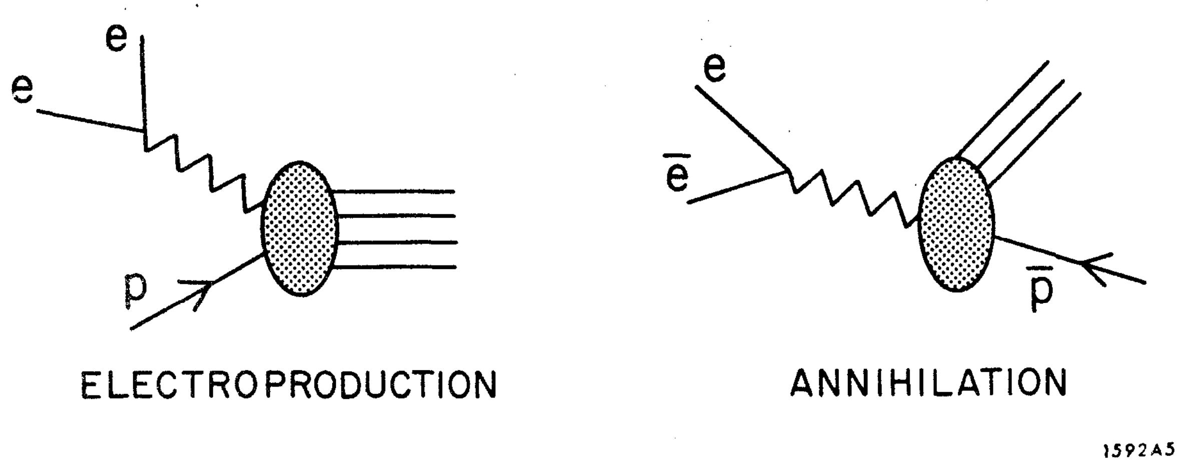


FIG. 6

$$\frac{d\sigma}{dE_{\bar{p}}} = \frac{1}{s}\, f\left(\frac{E_{\bar{p}}}{\sqrt{s}}\right) \tag{9}$$

The physical picture is that a bare $p\bar{p}$ pair is made by the photon as intermediate state.

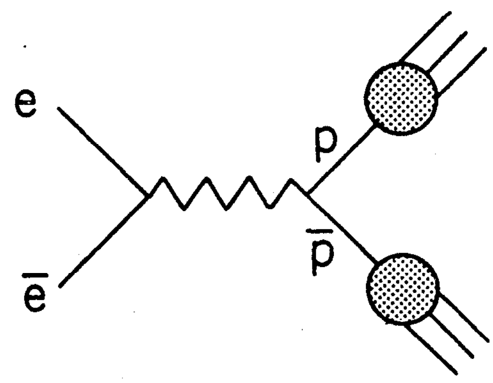


FIG. 7

They then dress themselves, with the average longitudinal fraction of emerging $\bar{p}$ not reduced by, say, more than a factor 2. The dressing operation also creates a cloud of pion secondaries along the direction of p and $\bar{p}$. Thus the principal feature of this model is that the distribution of secondaries is roughly similar to that found in $p\bar{p}$ collisions at high energies. In particular each event possesses an axis; the test in Section A, Eq. (5) might be used here. There should also be lots of $\bar{p}$'s produced.

The scaling phenomenon in the annihilation process is not a general consequence of scaling for the deep inelastic electroproduction. To see this, consider electroproduction from nuclei. Provided nucleon electroproduction scales, so will electroproduction from nuclei. But common sense tells us colliding beams will not produce anticarbon. The Drell, Levy, Yan result rests on the fact that their model contains the concept of bare proton. However, it is quite possible that other composite models (e.g., quarks) would lead to anisotropic distributions of secondaries, although in the case of quarks one expects the leading particles to be mesons, not baryons.

III. NEW ELECTRODYNAMIC TOPICS

A. New Particles

Of many proposed particles, some are closely associated with electromagnetic phenomena:

(a) Lee's a-particle,[26] coupled to the presumed C-violating piece of the electromagnetic current.

(b) The Lee-Wick[27] "ghost," an acausal heavy photon which cuts off electrodynamics divergences.

(c) Excited e* and μ^*, as in missing-mass experiments[28]

$$e + p \rightarrow e^* + p$$

$$\mu + p \rightarrow \mu^* + p$$

(d) Any new charged particles (heavy leptons, etc.) without strong interaction, via pair production.

These possibilities no doubt exclude what really happens!

B. High Transverse Momenta

The deep-inelastic electroproduction exhibits a large cross section for production of electrons with high $p_\perp$. There exist other processes where this phenomenon can be expected. These include, in addition to the neutrino-processes

$$\gamma + p \rightarrow \gamma + \text{hadrons} \quad \text{(a)}$$

$$\gamma + p \rightarrow \mu^+ + \mu^- + \text{hadrons} \quad \text{(b)}$$

$$\gamma + p \rightarrow \mu^- + \text{hadrons} \quad \text{(c)}$$

$$p + p \rightarrow \mu^+ + \mu^- + \text{hadrons} \quad \text{(d)}$$

Because the ferocious backgrounds associated with secondary hadrons disappear rapidly with increasing transverse momentum, at high energies these processes will be easiest to measure. For the first three, "high energies" may well mean a 100 GeV supercooled SLAC.

Experiment (a) tests the parton model. The prediction[7] is

$$\frac{\sigma_\gamma}{\sigma_e} \approx \frac{\langle \Sigma Q_i^4 \rangle}{\langle \Sigma Q_i^2 \rangle} \frac{\nu^2}{EE'} \tag{10}$$

i.e., comparable cross sections under the same kinematical conditions. Even if the parton-model is wrong the phenomenon may still exist. For example, if electroproduction goes diffractively in the sense of Fig. 8(a), then the process in Fig. 8(b) with a pointlike $\gamma\gamma q\bar{q}$ vertex may still lead to a large flux of secondary γ's with high $p_\perp$.

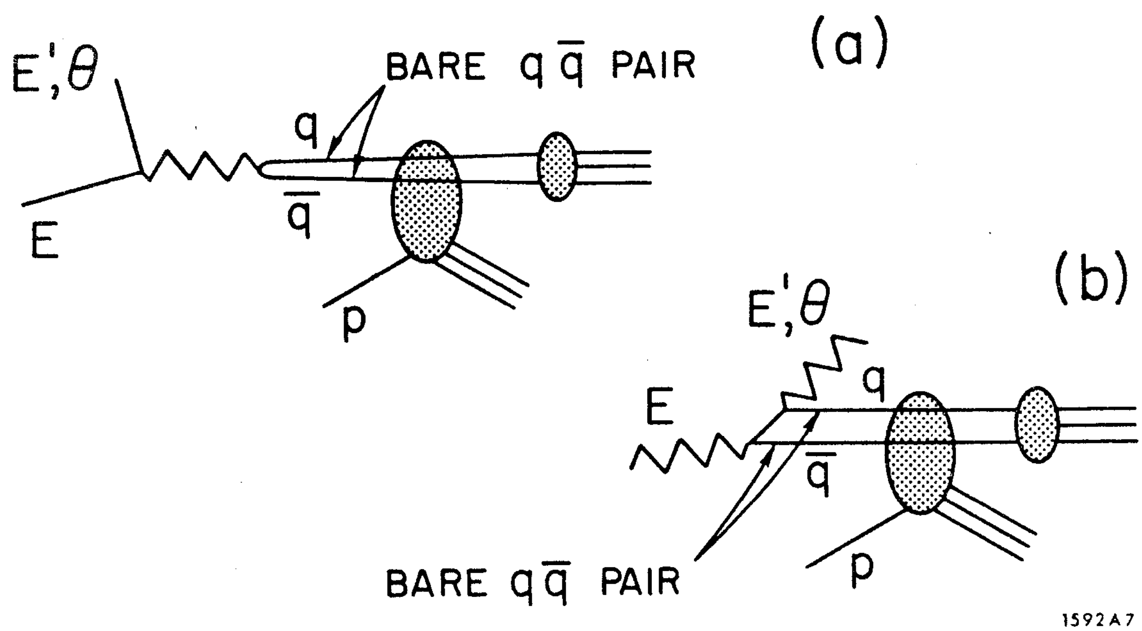


FIG. 8

Reaction (b) is a variant[29] of (a), with perhaps a better signature. One looks for μ-pairs of high $p_\perp$ but low invariant mass.

Reaction (c) is just wide-angle μ-pair production via the "bad" Bethe-Heitler graph (Fig. 9). The purpose is to measure deep-inelastic μ-p scattering. Just as an electron beam contains $\sim 1\%$ virtual photons, a photon beam contains $\sim 1\%$ virtual muons. Therefore, the virtual-muon flux at SLAC is $\sim 10^9$-10^{10} sec^{-1}, much more intense than "real" muon-fluxes. To use the virtual muons, one must go to high $p_\perp$ for the secondaries to get out from under the background from π^+ decay muons.

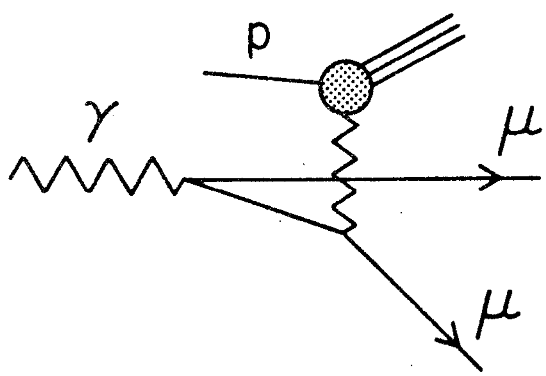


FIG. 9

Item (d) is an experiment recently completed at Brookhaven.[30] Parton-model calculations[31, 32] predict

$$\frac{d\sigma}{dm^2_{\mu\mu}} \approx \frac{1}{m^2 s} f\left(\frac{m^2}{s}\right) \tag{11}$$

This will be discussed more by Drell.[33] There are interesting reasons for this experiment other than checking parton ideas.

C. Coherent Phenomena in Nuclei

While not a new topic, the "shadowing" of photons absorbed on nuclei is a characteristically very high-energy effect. It has been extensively reviewed and has been discussed in this conference. But I cannot resist writing down a formula of Gribov's[34]

$$\sigma_{\gamma A} = \left(1 - Z_3^{\text{hadron}}\right) 2\pi R^2 \tag{12}$$

valid for $\lambda\!\!\!^{-}_{\gamma p} \gg R \gg \lambda\!\!\!^{-}_{\rho p}$ where $\lambda\!\!\!^{-}$ is the mean free path and R is the nuclear radius. Gribov also argues that in heavy nuclei, σ_S/σ_T increases with Q^2 much like the Sakurai prediction[35] for nucleons (which doesn't work).

D. Electrons as Targets

The reactions

$$\pi^+ + e \to \pi^+ + e$$

$$K^+ + e \to K^+ + e$$

$$K_L + e \to K_S + e \qquad \text{etc.}$$

at high energies measure the charge structure of π and K. They are discussed by Taylor[5] and Drell.[33]

E. Timelike Electromagnetic Form Factors

Discussion of future electrodynamic processes is not complete without at least mentioning two-body and quasi two-body baryon-antibaryon production in colliding e^+-e^- beams. Here there is a well-defined phenomenology,[20] a large battery of SU(3) predictions, and abysmally poor prediction of the absolute rates expected. But we should learn much from the next round of storage-ring experiments on these processes.

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