SPECULATIONS CONCERNING POSSIBLE NEW PHYSICS
FROM EXPERIMENTS ABOVE 10TeV[*][†]

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We can classify the kinds of new physics which we can hope to learn from experiments at higher energies -- from cosmic rays and from colliding beam accelerators -- into two categories.

(A) Standard experiments. These include a number of important areas which have been well studied and reviewed already, such as (a) measurement of σ_{TOT}, scaling and scaling violations, and related "ℓns" physics; (b) production of gauge bosons $W^{\pm}, Z^{\circ}$; and (c) large p_T data resulting from basic constituent interactions. Since these have been well covered I will on the whole not discuss them here.

(B) Other. There are a number of possible new kinds of effects. Of course, one could speculate without constraint, but today one has available viable gauge theories of strong, weak, and electromagnetic interactions and it seems preferable to speculate within the context of these new effects. It may be that none of the following speculations will be realistic and we are only free to discuss them at the moment because our understanding of the theory is minimal. Even so, some good, either theoretical or experimental, may come from such considerations.

The topics I will discuss are
(1) Possible large "weak interactions" at very high energies, with an associated cross section that is a significant part of σ_{TOT}; what characteristics would enable us to detect such new effects?
(2) Can we learn some things about QCD and gluons from small p_T , large cross section experiments?

(3) At large p_T but very high energy, cross sections in QCD get very large.

(4) Some new heavy meson excitations are suggested by increased understanding of the gauge theories and could appear experimentally.

LARGE "WEAK INTERACTIONS" AT VERY HIGH ENERGIES

What happens at very high energies in the unified gauge theories of weak and electromagnetic interactions? First, consider the Weinberg-Salam theory,[1] with a single Higgs boson doublet to provide the masses of the gauge bosons ($W^{\pm}$, Z°) and the fermions, via spontaneous symmetry breaking. Suppose the Higgs boson masses are not large, i.e. $m_H \lesssim m_W$. Then it can be shown that no weak interaction effects get large. At very large p_T, for example, the weak and electromagnetic cross sections will be comparable in size. The weak interaction will be relatively isotropic, so it is a tiny part of the cross section at small p_T, and thus a tiny part altogether.

However, if $m_H \gg m_W$, some amplitudes in the boson sector become larger[2,3], because the coupling strengths are proportional to m_H. Then one can imagine obtaining large cross sections. It is interesting to consider ways to observe possible "weak" effects at very high energies. Before we do that, briefly consider how such effects could be imagined to arise.

Consider Higgs boson scattering via an s-channel Higgs,
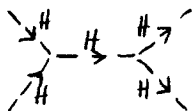
giving an amplitude

$$M = \frac{9}{4} g^2 \frac{m_H^2}{m_W^2} \frac{m_H^2}{s-m_H^2} = 18 \ (G_F \ m_H^2) \ m_H^2/(s-m_H^2)$$

and a cross section

$$\sigma = \frac{81}{4\pi s} \ (G_F \ m_H^2)^2 \ \frac{(m^2 H)^2}{(s-m_H^2)^2} \ .$$

If we assume $m_H = 1$ TeV $= \sqrt{s}$, an energy which can be achieved by the colliding doubler at FNAL even for constituent subenergies, and put $s - m_H^2 \simeq m_H \Gamma_H$, then $\sigma \simeq 260$ mb$/\Gamma_H^2$ with Γ_H in GeV. Such a cross section greatly exceeds the unitarity limit, since it arises from a single partial wave. Similar results arise for other diagrams. Consequently they will be suppressed. Nevertheless, it is conceivable that the dynamics gives rise to amplitudes from the Higgs sector which are large enough to give observable effects, directly or through interferences with strong interactions.

Is this relevant to experiments? Here a subtle complication arises -- in the simplest Weinberg-Salam theory, with one Higgs doublet, even if large effects did arise the answer is no.[2,4] To do experiments one must begin with fermions; e.g. $q\bar{q}$ or e^+e^- collide (the $q\bar{q}$ in hadrons). Then all of the large amplitudes get multiplied by the tiny factor $(m_f/m_W)^2$, essentially because that factor appears in the Higgs-fermion coupling. One can make a strong statement: in the standard theory at high energies there will be no weak interaction effects not directly due to production of W's and Z's; observation of such effects would contradict the standard theory.

Is this general? No. One can construct theories[5,6,7,8] which differ only in the Higgs sector, in which the Higgs-fermion coupling is no longer suppressed by the factor m_f/m_W. In essence one needs two Higgs doublets, one having vacuum expectation value v and giving mass to fermions, with $v \sim m_f$, and the other having vacuum expectation value V and giving mass to the gauge bosons, with $V \sim m_W$. No contradiction with experiment arises[8] for Higgs-fermion couplings up to about two orders of magnitude times that of the standard theory. While an extension of the standard theory along these lines is not required by any data, it is of interest to have the boson and fermion mass scales set separately in the Higgs sector. If nature were like this extension it would be relatively easy to detect Higgs bosons and their effects, and -- most relevant here -- it is not prohibited from giving large cross sections associated with the Higgs sector at high energies.

So far I have argued that even within the context of the conventional gauge theories it could happen that large cross sections arise from effects associated with the Higgs sector. The arguments are meant to stimulate our thinking rather than to lead to definite conclusions; they certainly do not imply that such effects will be present. More important is the question: how could we detect large Higgs-related phenomena if they were present?

To give some answers to this, consider the characteristics of normal strong interactions at present experimental energies:

(a) Hadrons have a certain size, and differential and total cross sections are qualitatively fixed by geometrical arguments, $\sigma_{TOT} \simeq \pi R^2$, $d\sigma/dt \simeq \sigma_{TOT}^2 \exp(R^2 t)$ $d\sigma/dt$ also has a diffraction minimum.

(b) Isospin is a good symmetry

(c) Parity is a good symmetry

(d) Large p_T events are very improbable

(e) Increased energy input goes mainly into relative motion, not into particle masses and increased multiplicity. Consequently, multiplicity grows as ℓns.

If a new interaction (e.g. related to the Higgs sector as above) becomes important at very high energies there is no guarantee that it will respect any of these results. Consider them in turn.

(a) If a new interaction is present it could have a distance scale which is not connected to normal hadronic sizes. Then σ_{TOT} could change[9] fairly abruptly to a new value; presumably only an increase will occur as a different distribution in partial waves would be involved and cancellations are unlikely. Similarly, $d\sigma/dt$ could broaden significantly if a part of the cross section involved scattering on a shorter distance scale. (In this context it is amusing that recent data[10] shows a relatively isotropic $d\sigma/dt$ for pp elastic scattering at 400 GeV/c, with $d\sigma/dt \sim \exp(0.7t)$ for $-t \simeq 10$ GeV^2, while for small t, $d\sigma/dt \sim \exp(12t)$.)

(b) Since Higgs-quark couplings are proportional to the quark mass, and[11] $m_u \neq m_d$, the Higgs-quark interaction does not conserve isospin. If it led to large high energy interactions, one might find

large isospin violations at such energies. For example,
one could find

$$\sigma_{TOT}(pp) \neq \sigma_{TOT}(np) \neq \sigma_{TOT}(pd)/2$$

or

$$n(\pi^\circ) \neq (n(\pi^+) + n(\pi^-))/2$$

with similar results for other resonances. At present
there is no way to estimate what effects to expect
(if any); the key point is that such effects could
occur and we should be alert to find them.

(c) In a similar way it could happen that large
parity-violation effects occur at high energies. For
example, to give an illustrative mechanism, in the
model of Ref. 8 the charged Higgs can be quite massive
and it couples only to left-handed fermions. There
are several ways[12] to detect such effects.

-- If a Λ is detected, it has a decay angular
distribution

$$W_\Lambda(\theta,\phi) = N \left\{ 1 + \alpha \sin\theta \sin\phi \, P_y + \alpha \sin\theta \cos\phi P_x \right.$$

$$\left. + \alpha \cos\theta P_z \right\},$$

where θ,ϕ are the decay angles in the Λ rest frame,
$P_{x,y,z}$ the components of the Λ polarization, and α the
measured asymmetry, $\alpha \simeq 2/3$. If parity is conserved
in the production of the Λ, then $P_x = P_z = 0$. Thus
the presence of the $\sin\theta \cos\phi$ or $\cos\theta$ terms would
require parity violation in the production. A non-zero
P_z could occur from direct "weak" production of the Λ,
while a non-zero P_x would have to arise from interference
of a parity-violating and a parity-conserving amplitude
of non-zero radative phase. Similar results[12] hold
for production of ϕ, K^*, ρ, Δ, ... In general it is
possible to learn from the strong decay angular
distribution of a resonance if its production was parity
violating.

-- One can form parity-violating observables
such as

$$\left\langle \vec{p}_{\pi^+} \times \vec{p}_{\pi^-} \cdot \vec{p}_{beam} \right\rangle .$$

and look for non-zero values.

-- Consider a large p_T quark jet, which fragments into two (π_a, π_b) or more pions. Then the angular correlations of $\vec{p}_a$, $\vec{p}_b$ may allow the determination[13] of longitudinal and transverse polarizations of q.

(d) A new mechanism associated with Higgs or "weak" interactions could presumably lead to different behavior at large p_T. This could get confused with the changes in large p_T behavior expected from QCD when hard scattering of constituents takes over (see below), and it will be important not only to look for changes at large p_T but to check whether the usual strong interaction symmetry laws apply, as expected in QCD.

(e) Finally, if a new mechanism enters there is no reason for the energy dependence of the multiplicity to stay the same. There could also be different multiplicity growth in different regions. Of course, it could happen that accidently two different mechanisms gave the same growth, or, multiplicity changes could be an easily detected clue to new phenomena.

How likely is any of the above scenarios? Although they are plausible, presumably they are not very likely. But the important thing is that the absence of any new effects at very high energies would also tell us a great deal about how the theory develops. Since good theories exist now, it is of great value to confirm their predictions, and to help guide their application in areas where calculations are difficult.

Low p_T QCD

Next turn to possible ways of learning about gluons and QCD from small p_T information. This is not as good as looking directly at perturbative QCD arguments and experiments directly related to qq or qg collisions. However, there may be useful physics to be learned, and a good deal of the total cross section is relevant

to this region so it merits serious study.[14,15].
I'll mention three possibilities.

(a) It may be that single gluons give rise to the
central region clusters.[14,15] An important test of this
is their flavor neutrality if they originate solely from
gluons. Theoretically, it will eventually be possible to
calculate multiplicities, mass distributions, rapidity
gap distributions in terms of QCD quantities. These
will have some s-dependence -- at higher energy, are
there more clusters with energy-independent characteristics,
or do the characteristics change too?

(b) An important possibility may be the opportunity
to directly measure the gluon distribution function in
the most important region of x, around $x \simeq 1/3$. To see
this, consider particle ratios in central region production.

Since hadrons from gluons will be flavor neutral, ratios
such as π^+/π^-, K^+/K^-, $\bar{p}/p$, $\bar{\Lambda}/\Lambda$ must go to one if the
hadrons come from gluons.

Normally it is very hard to measure the gluon
distribution function, i.e. the probability of finding
gluons with a fraction x of the hadrons momentum $G(x)$,
because weak and electromagnetic currents do not interact
with gluons. Consider the curves in Figure 2,
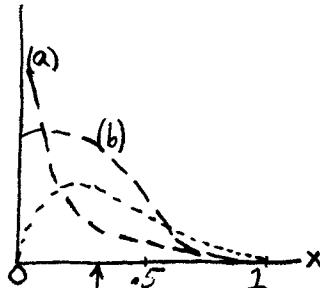
where the dashed lines show two possible gluon functions
(a), and (b), and the dotted line the valence quark
distribution. Look at $x \simeq 0.3$ (the arrow). Then for
distribution (a) the quarks dominate over the gluons,
and the particle ratios will not be unity, nor will they
get closer to unity as s increases and the gluons have
more opportunity to dominate the central region. But
for distribution (b), the gluons dominate over the quarks,
and as s increases the particle ratios will get closer
to unity at this x value. At each x, we can determine
whether $G(x) >> q(x)$, $G(x) \simeq q(x)$, or $G(x) << q(x)$.

Since $q(x)$ is measured in lepton reactions, and the area under $G(x)$ is known from the momentum sum rule, this effectively allows a useful determination of $G(x)$. Data at current energies suggests that such a procedure may work at higher energies.

(c) An important prediction of QCD is that gluon-gluon interactions will be strong, and that probably resonant states -- called glue-balls -- will be formed. Although this subject is not well understood[16] most work indicates that σ_{gg} will be large, with several low-spin, low-mass resonances. Perhaps it will look as in Figure 3, where the dashed line indicates the unitarity limit.
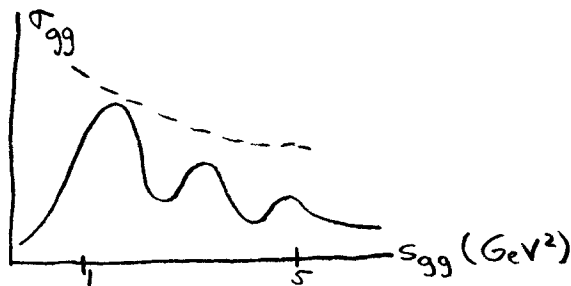
Solutions to QCD will have definite predictions for σ_{gg} as well as the gluon distribution functions. One possible indirect way to probe these is via the behavior of the very high energy total cross section. If we assume part of σ_{TOT} is due to gluon-gluon interactions, we can write that part as

$$\Delta\sigma_{TOT}^{G} = \int dx_1\ dx_2\ G(x_1)\ G(x_2)\ \sigma_{gg}(x_1 x_2 s)$$

Where $G(x_1)$ gives the probability of finding one gluon with momentum fraction x_1 in one hadron, and similarly for $G(x_2)$. One can argue[15] that the observed rise in σ_{TOT} is due to such a mechanism. For example, at low energies and typical x values, σ_{gg} is small. At higher energies σ_{gg} is in the region of its unitarity limit and $\Delta\sigma_{TOT}^{G}$ is large. If $G(x) \sim 1/x$ for small x, as is expected, then $\Delta\sigma_{TOT}^{G}$ grows as ℓns ($\ell n^2 s$) if σ_{gg} falls (becomes constant) at large s. The absolute size calculated from the above formula is consistent with what is needed to

explain ISR data, assuming a σ_{gg} with a few low energy resonances. Thus eventually, as we understood QCD better, it may be possible to predict the size and s-dependence of σ_{TOT} at very high energies in terms of low energy gluon properties.

LARGE p_T QCD

Finally I will give a few remarks from a conventional large p_T QCD viewpoint. These are based on calculations from R. Field[17]. The main point is that at very high energies QCD predicts that the large p_T cross section will be rather large. FOr example, the inclusive π° cross section has the property

$$E \frac{d\sigma}{d^3 p} \quad (\pi^\circ, \ p_T = 30 \text{ GeV/c}, \ 90^\circ, \ \sqrt{s} = 500 \text{ GeV})$$

$$\simeq E \frac{d\sigma}{d^3 p} \quad (\pi^\circ, \ p_T = 6, \ 90^\circ, \ \sqrt{s} = 19.4).$$

Similarly, the cross section for pp $\rightarrow$ a jet with $p_T > 2$ GeV has risen from of order 1% of σ_{TOT} at (say) $\sqrt{s} = 15$ GeV, to as much as 40% of σ_{TOT} for $\sqrt{s} = 800$ GeV.

These cross sections are large because the cross section grows and approaches a p_T^{-4} fall off as the energy increase. This is due in part to the asymptotically free nature of the theory. It is also kinematic in part, with interactions occuring at parton x values more toward the maxima of the parton distributons as more energy is available and the kinematic restrictions matter less.

It will be of great importance to check these rather dramatic predictions.

HEAVY MESONS

Just as glueballs arise from the interactions of the quantum in QCD, analagous excitations will be found in Weinberg-Salam theory. Recently, Nambu[18] has shown that classical solutions representing monopole-antimonopole configurations may be stable or nearly so and may give particle or resonance solutions. Einhorn and Savit have shown[19] that stable configurations of Z°-flux may exist as particle states (Z°-balls). These

could decay into several Z°'s plus whatever states Z°
is strongly coupled to, such as fermion-antifermion pairs.

So far, the arguments used by the above authors have
been made for classical solutions, which correspond to
highly excited states. However dimensional arguments
alone indicate that the masses would be large, of order
1 TeV. Whether production cross sections will be large
enough to lead to observation of such states is not
known, but is not excluded. Both theoretically and
experimentally, the existence of such states in the
spectrum of gauge theories must be taken seriously.

CONCLUSIONS

Even within the framework of the conventional gauge
theories it could happen that rather surprising behavior
is in store at very high energies, including significant
changes in σ_{TOT} and $d\sigma/dt$, and large parity or isospin
violations. On the other hand, perhaps no new kinds of
effects occur. The latter alternative should not be con-
sidered boring; it has implications for the development
of the gauge theories that are just as interesting and
important as if some dramatic new behavior is found.

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