Fermi National Accelerator Laboratory

FERMILAB-Pub-91/58-T
March, 1991

GAUGE BOSON DYNAMICS

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ABSTRACT

Greater understanding of the connection between the weak and electromagnetic interactions is central to progress in elementary-particle physics. A definitive exploration of the mechanism for electroweak symmetry breaking will require collisions between fundamental constituents at energies on the order of 1 TeV. I report on the prospects for learning about electroweak dynamics from the scattering of gauge bosons at low energies.

1. Introduction

If, one morning in the year 2002, we see on our computer screens a histogram of gauge-boson pairs in the ($I = 0, J = 0$) channel resembling the one in Figure 1, what will we be able to conclude? That question has been much on my mind of late, as preparations begin in earnest for experiments that will explore the 1-TeV scale. I haven't yet found a satisfying answer, but because the problem is both interesting and important, I want to present some of my incomplete thoughts.

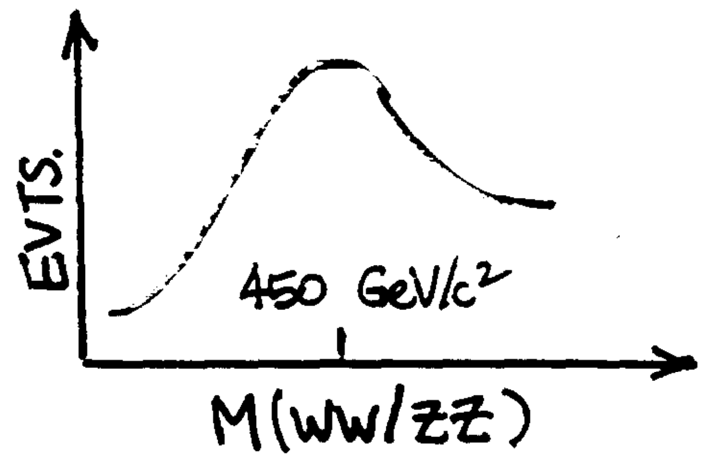

Figure 1. Experimental results (ca. 2002) on the scattering of electroweak gauge bosons.

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I will suspend for this talk the requirement of actually doing experiments so we may concentrate on the theoretical essentials. I therefore defer significant—and much studied—practical problems: detecting W and Z with high efficiency, separating the nonresonant background, and achieving adequate luminosities for gauge-boson scattering.

Some of the specific questions I want to explore are these: • What can we learn about dynamics by measuring WW scattering at energies below 1-TeV? • Is the effective Lagrangian approach more controlled, or more general, than specific models? • What sources of uncertainty soften predictions from models or cloud the interpretation of data? • What lessons about broad hadronic resonances should we have in mind as we begin studying WW spectroscopy?

To open the discussion, I describe circumstances under which electroweak gauge bosons may interact strongly. After recalling the equivalence theorem, I summarize recent results on higher-order corrections to gauge-boson scattering and compare their effects to the influence of unitarity. A brief review of chiral Lagrangians for $\pi\pi$ scattering leads to the application of chiral perturbation theory to WW scattering. A statement of tentative conclusions closes the paper.

2. Strong Scattering of Gauge Bosons

Unitarity arguments[1] show that, if the mass of the Higgs boson becomes large, the interactions among electroweak gauge bosons may become strong at high energies.[2] It is straightforward to compute the amplitudes $\mathcal{M}$ for gauge-boson scattering at high energies and to make a partial-wave decomposition according to

$$\mathcal{M}(s,t) = 16\pi\sum_{J=0}^{\infty}(2J+1)a_J(s)P_J(\cos\theta) \quad . \tag{1}$$

Most channels "decouple," in the sense that partial-wave amplitudes are small at all energies (except very near the particle poles, or at exponentially large energies), for any value of the Higgs boson mass M_H. Four neutral channels involving longitudinally polarized gauge bosons (denoted by the subscript L) are interesting:

$$\begin{array}{c} W_L^+W_L^- \\ Z_LZ_L/\sqrt{2} \\ HH/\sqrt{2} \\ HZ_L \end{array} \quad , \tag{2}$$

where the factors of $\sqrt{2}$ account for identical-particle statistics. For these, the s-wave amplitudes are all asymptotically constant (i.e., well-behaved) and proportional to $G_FM_H^2$. In the high-energy limit,

$$\lim_{s \gg M_H^2} (a_0) \to \frac{-G_F M_H^2}{4\pi\sqrt{2}} \begin{bmatrix} 1 & 1/\sqrt{8} & 1/\sqrt{8} & 0 \\ 1/\sqrt{8} & 3/4 & 1/4 & 0 \\ 1/\sqrt{8} & 1/4 & 3/4 & 0 \\ 0 & 0 & 0 & 1/2 \end{bmatrix} . \quad (3)$$

Requiring that the largest eigenvalue respect the partial-wave unitarity condition

$$|a_0| \leq 1 \quad (4)$$

yields

$$M_H < \left(\frac{8\pi\sqrt{2}}{3G_F}\right)^{1/2} = 1 \text{ TeV}/c^2 \quad (5)$$

as a condition for perturbative unitarity. If the bound is respected, weak interactions remain weak at all energies (except near particle poles), and perturbation theory is everywhere reliable. If the bound is violated, perturbation theory breaks down, and weak interactions among $W^{\pm}$, Z, and H become strong on the 1-TeV scale. We interpret this to mean that new phenomena are to be found in the electroweak interactions at energies not much larger than 1 TeV.

The requirement (4) that the modulus of the s-wave elastic scattering amplitude be less than unity is only the crudest statement of the unitarity constraint. The precise requirement, shown in Figure 2, is that a_0 must lie within the unitarity circle of radius 1/2 centered at $(0,\frac{1}{2})$. Since we are dealing with lowest-order "Born" amplitudes that are purely real, it may be reasonable[3] to require that $|a_0| \leq \frac{1}{2}$, which tightens the bound on M_H. What is important for us today is that the scattering of gauge bosons *might* become strong.

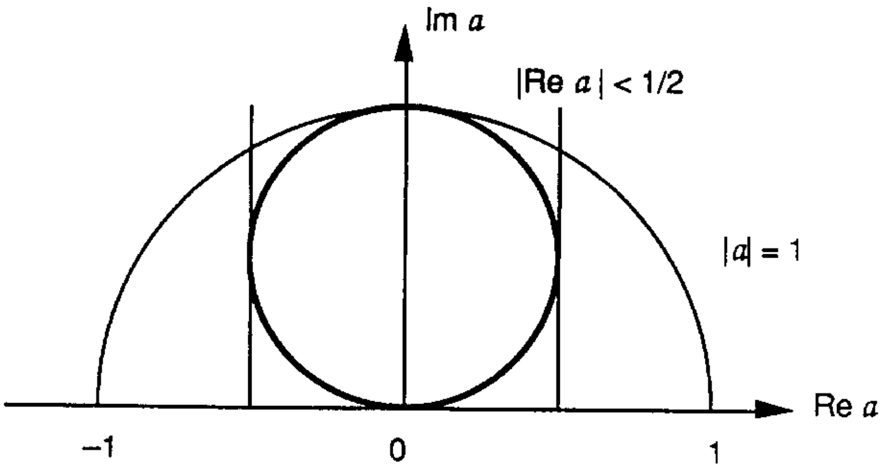

Figure 2. Partial-wave unitarity constraints for elastic scattering amplitudes.

What could it mean if partial-wave amplitudes become large and gauge-boson scattering becomes strong? One possibility is that the minimal standard model—or some straightforward generalization—is correct, but that it cannot be solved perturbatively. Several lines of attack would then be open to us. (i) We could guess the answer by analogy with a familiar example of strongly interacting bosons, by mapping

$$\begin{aligned} \pi &\rightarrow W \\ \text{GeV} &\rightarrow \text{TeV} \end{aligned} \quad . \tag{6}$$

That would suggest the existence of WW resonances and the multiple production of gauge bosons in WW collisions at energies of around 1 TeV. (ii) We could unitarize perturbation theory. (iii) We could capture the essence of the theory—imposed by symmetry requirements—in an effective Lagrangian, and unitarize that. This would be equivalent to unitarizing perturbation theory for $s \ll M_H^2$. (iv) Finally, we could attempt to solve the strongly interacting theory on the lattice.

(Desirable as a nonperturbative solution might be, I do not understand how to formulate the problem of gauge-boson scattering on the lattice in a way that makes sense. The theory is not asymptotically free, so it is not possible to take the continuum limit in the usual way. However, extensive analytic[4] and numerical[5] calculations of the standard model on the lattice suggest that the cutoff parameter in the lattice regularization can be substantially greater than the Higgs-boson mass only if the mass does not significantly exceed $640 \pm 40\ \text{GeV}/c^2$.)

A second possibility is that the Higgs boson is not an elementary scalar. We can pursue this idea by making a specific alternative theory. We may try to solve it directly, or to guess a solution in analogy with QCD. Instead, we may try to capture the essence of the theory in an effective Lagrangian, and unitarize that.

Early work was concentrated on specific models. More recently, there has been heightened interest in the effective Lagrangian approach, which derives its appeal from successful applications to $\pi\pi$ scattering and from the possibility that symmetries essentially determine the outcome in an interesting region above threshold.

3. Beyond the Born Approximation

To discuss the strong scattering of electroweak gauge bosons, it is convenient to idealize the gauge bosons as massless,

$$M_W = M_Z = 0 \quad , \tag{7}$$

and to use the equivalence theorem[6]

$$\mathcal{M}(W_L, Z_L) = \mathcal{M}(w, z) + O(M_W/\sqrt{s}) \tag{8}$$

to reduce the dynamics of longitudinally polarized gauge bosons to a scalar field theory with interaction Lagrangian given by

$$\mathcal{L}_I = -\lambda v h(2w^+w^- + z^2 + h^2) - \frac{\lambda}{4}(2w^+w^- + z^2 + h^2)^2 \quad , \tag{9}$$

where

$$\begin{aligned} 1/v^2 &= G_F\sqrt{2} \\ \lambda &= G_F M_H^2/\sqrt{2} \quad . \end{aligned} \tag{10}$$

One-loop corrections to gauge-boson scattering have been computed recently by a number of authors.[7–11] Several conclusions are relevant to the present discussion of a strongly interacting gauge sector. First, the effects are in general small for $\sqrt{s} \lesssim 1/2$ TeV, even for quite large values of M_H. Second, one-loop corrections restore perturbative unitarity up to energies of a few TeV, for $M_H \lesssim 300$ GeV/c^2. What is most important for our considerations is that the effect of one-loop corrections on unitarized amplitudes is small, until $\sqrt{s}$ greatly exceeds the Higgs-boson mass.[8] At such high energies—which may not be accessible for gauge-boson scattering even at the SSC—elastic unitarity is unlikely to be a realistic approximation for a strongly interacting theory. Indeed, there may be many influences that mask—or compete with—the effects of loop corrections.

Willenbrock and Valencia[12] have examined higher-order effects on the Higgs-resonance line shape. Their conclusion that the resonance line shape peaks above the Higgs-boson mass is shared by any unitarization procedure that develops an energy-dependent width, broadening the high side of the resonance. But experience in hadron spectroscopy teaches that the high side of a resonance line may be narrowed by the next resonance in the channel. If a channel supports only a single resonance, at energy $E = M_1$, then the phase shift δ will pass through $\pi/2$ at the resonance energy and approach the value $\delta = \pi$ at infinite energy. However, if there is a second resonance in the same channel at energy $E = M_2$, the phase shift will pass through $3\pi/2$ at $E = M_2$. To do so, it must have passed through the value $\delta = \pi$ in the interval $M_1 < E < M_2$, hastening the descent of the cross section from the first resonant peak. (It is instructive to see the possible effects by making a K-matrix unitarization of a sum of Breit-Wigner resonances with energy-dependent widths.) Would the observation of a broad but symmetrical WW resonance signal multiple resonances in the channel? Might the dual resonance model[13] for $\pi\pi$ scattering hold valuable lessons for WW interactions?

4. $\pi\pi$ Scattering and Chiral Lagrangians

Chiral perturbation theory is widely used to calculate matrix elements involving low-energy pions. The method consists of writing down chiral Lagrangians[14–16] for the physical processes and expressing the matrix element as a power series of the kinematical invariants. The lowest-order effective Lagrangian for $\pi\pi$ scattering occurs at order energy^2. It is prescribed by $SU(2)_L \otimes SU(2)_R$ chiral symmetry as

$$\mathcal{L}_1 = \frac{f^2}{4}\,\mathrm{Tr}(\partial_\mu U \partial^\mu U^\dagger) + \frac{m^2 f^2}{4}\,\mathrm{Tr}(U + U^\dagger) \quad , \tag{11}$$

where the $SU(2)$ matrix

$$U = \exp\left(\frac{i\vec{\pi}\cdot\vec{\tau}}{f}\right) \, , \tag{12}$$

with $\vec{\pi}$ the pion field and $\vec{\tau}$ the Pauli isospin matrix, transforms under $SU(2)_L \otimes SU(2)_R$ as $U \to L^\dagger U R$. This means that all of pion physics near threshold is specified in terms of the two parameters m and f. Weinberg's classic results[17] are recovered by identifying these as the pion mass m_π and the pseudoscalar decay constant f_π.

At order energy^4, the effective Lagrangian is $\mathcal{L} = \mathcal{L}_1 + \mathcal{L}_2$, where[18]

$$\begin{aligned}\mathcal{L}_2 = {} & A\,[\mathrm{Tr}(\partial_\mu U \partial^\mu U^\dagger)]^2 + B\,[\mathrm{Tr}\partial_\mu U \partial_\nu U^\dagger][\mathrm{Tr}\partial^\mu U \partial^\nu U^\dagger] \\ & + C\,m^2\,[\mathrm{Tr}(\partial_\mu U \partial^\mu U^\dagger)(U + U^\dagger)] \\ & + D\,m^4\,[\mathrm{Tr}(U)]^2 + E\,m^4\,[\mathrm{Tr}(\tau_3 U)]^2 \end{aligned} \quad . \tag{13}$$

The coefficients A, B, C, D, and E characterize the low-energy behavior of different theories of dynamically broken chiral symmetry. The final (E) term, which arises from second-order isospin breaking, is negligibly tiny. Scattering amplitudes depend explicitly only on A and B; an implicit dependence on C and D enters the relation between (m, f) and (m_π, f_π). We can hope to distinguish rival models by determining the coefficients from measurements of $\pi\pi$ scattering. Eventually, we can hope to calculate them from the theory of the strong interactions, QCD.

Two groups[19,20] have recently analyzed results on $\pi\pi$ scattering in the framework of chiral Lagrangians. In broad terms, the data can be understood not only at threshold but also up to energies of 0.7–0.9 GeV, and have some power to determine A and B. Differences between the two analyses call attention to the effects of different procedures for unitarizing the amplitudes. In the case of gauge-boson scattering, for which we do not yet have recourse to data, the dependence of theoretical results on unitarization scheme limits our confidence in predictions.

5. Chiral Lagrangians for Gauge-Boson Scattering

The application of chiral perturbation theory to the scattering of intermediate bosons begins with the observation that the low-energy behavior of partial-wave amplitudes a_{IJ} in the standard model,

$$
\begin{aligned}
a_{00} &\sim G_F s/8\pi\sqrt{2} && \text{attractive} \\
a_{11} &\sim G_F s/48\pi\sqrt{2} && \text{attractive} \quad , \\
a_{20} &\sim -G_F s/16\pi\sqrt{2} && \text{repulsive}
\end{aligned}
\tag{14}
$$

follows generally from global chiral symmetry.[21,22] If $\pi\pi$ scattering is a reasonable model for WW interactions, chiral perturbation theory may provide a precise framework for the mapping

$$
\begin{array}{c}
\pi \quad \leftrightarrow W \\
\text{GeV} \leftrightarrow \text{TeV}
\end{array}
\quad .
\tag{15}
$$

There are, however, some important distinctions between the two cases. Chiral perturbation theory for $\pi\pi$ scattering was developed long before QCD was recognized as the theory of the strong interactions. A complete solution of QCD still eludes us. In contrast, while it may be incomplete (or at least incompletely specified), the standard model of the electroweak interactions is known. If a perturbative solution is not apt, we can base QCD-like models on Nature's solution to QCD, even if we cannot yet solve the theory ourselves.

The transcription from $\pi\pi$ scattering to WW scattering[23–25] entails changing the Lagrangian by replacing the pion field by the W field and substituting $v = 246$ GeV for f_π. Two classes of models have been studied, to exploit the generality of the chiral perturbation theory framework:

- "Higgs-like" models, with parameters extracted from the low-energy limit of one-loop standard-model amplitudes. These are characterized by parameters $A \gg B$.
- "QCD-like" models, with parameters either scaled from chiral-perturbation-theory fits to $\pi\pi$ scattering or taken from technicolor theories. We may think of these as realizations of $SU(3)_{TC}$ or $SU(N)_{TC}$ theories, respectively. They are characterized by $A \approx -B > 0$.

Applications to supercollider experiments have been made by several groups.[26–30]

Although the effective Lagrangian approach is general, in the sense that correct low-energy behavior is ensured and variations of the parameters A and B tune from one theory to another, it has important limitations. One is that a power-series expansion in s necessarily omits features that may be characteristic of dynamics. For example, chiral perturbation theory yields featureless partial-wave amplitudes that do not display resonant features. A "Higgs-like" theory will contain no Higgs scalar; a "QCD-like" theory will contain no technirho. The structures we expect to differentiate mechanisms for spontaneous symmetry breaking occur at energies far above threshold, where an expansion including terms through s^2 is an inadequate representation of the full theory.

We might still hope that measurements of the WW mass spectrum and partial-wave amplitudes at energies below the resonance region might distinguish among theories and allow us to anticipate the behavior at higher energies. I doubt that this will be successful, because of a second shortcoming of the method. At just the energies at which chiral-perturbation-theory representations of rival dynamical schemes begin to diverge, the partial-wave amplitudes threaten unitarity constraints. Since we do not know how to solve the dynamics exactly, we must enforce unitarity by following some procedure that is inevitably chosen *ad hoc*. In all the work done until now, unitarity is understood to mean *elastic* unitarity, which is only strictly true for $4M_W^2 < s < 16M_W^2 = (0.32\text{ TeV})^2$.

In our early studies of strongly interacting gauge bosons in the standard model,[31] we took a page from 1960s work on $\pi\pi$ scattering and enforced elastic unitarity through a first-order (determinantal) N/D equation. The unitarized partial-wave amplitude is written as

$$a_{00}^{U} = \frac{N(s)}{D(s)} \quad , \tag{16}$$

where the numerator function $N(s)$ contains only left-hand branch cuts and the denominator function $D(s)$ has only the right-hand cut. A single iteration leads to

$$a_{00}^{U} = \frac{G_F s/8\pi\sqrt{2}}{\left[1 - s/M_H^2 + (G_F s/8\pi^2\sqrt{2})\log(-s/M_W^2)\right]} \quad . \tag{17}$$

The logarithm in the denominator shifts the pole from the position M_H of the Higgs scalar in the Lagrangian and gives the amplitude an imaginary component. The N/D treatment is an improvement over lowest-order perturbation theory, but is impotent when faced with the really interesting question "What happens when M_H is large compared to 1 TeV/c^2?" as a glance at Figure 2 of Reference 31 will confirm. Therefore one problem—not restricted to chiral perturbation theory—is that unitarization procedures cannot substitute entirely for dynamical solutions.

A second serious problem is that different unitarization procedures lead to different results. This is nicely illustrated by the work of Dobado, Herrero, and Terron,[32] who compared K-matrix and Padé approximant methods. The partial-wave amplitudes displayed in Figure 3(a)–(c) show that, for a Higgs-like model with $M_H \gg 1$ TeV/c^2, the Padé method may produce an s-wave resonance peak in the neighborhood of 1 TeV/c^2, while the K-matrix yields featureless amplitudes.

The Padé result supports an old prejudice of mine, that—in the standard model—a Higgs scalar would be found below about 1 TeV/c^2, whether it was present in the Lagrangian or not. It has seemed reasonable to me to believe that, as $M_H \to \infty$ in the Lagrangian, the Higgs surrogate would move to lower masses, as these results indicate. The K-matrix results, on the other hand, suggest that my intuition is misguided.

The situation is similar for the (1,1) partial wave in a QCD-like model, as shown in Fig. 3(d): the Padé method produces a technirho resonance, but the K-matrix method does not. It is unsatisfactory that in a model intended to emulate technicolor the existence of technivector mesons should depend on the unitarization scheme. I conclude that the information lost in going from a definite model to an effective Lagrangian outweighs the potential benefits of the chiral perturbation theory approach.

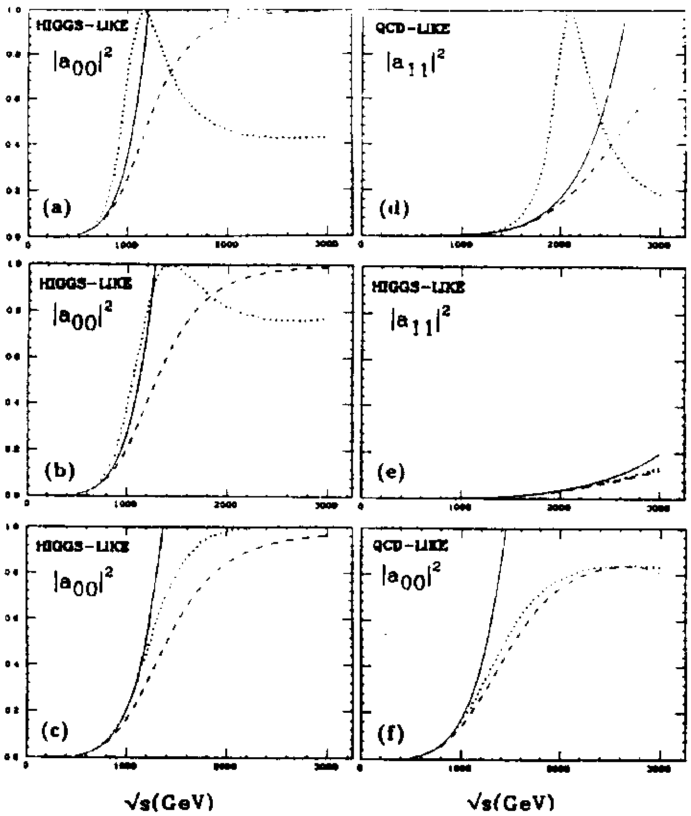

Figure 3. Energy dependence of (I,J) = (0,0) and (1,1) partial-wave amplitudes for two classes of models and two unitarization procedures. Solid lines represent the amplitudes given by chiral perturbation theory. Dotted lines show amplitudes unitarized by Padé approximants, and dashed lines are amplitudes unitarized by K-matrix methods. Cases (a), (b), (c) correspond to effective Lagrangians for Higgs scalars with masses M_H = 20, 15, and 5 TeV/c^2. Plots (d), (e), and (f) all correspond to M_H = 20 TeV/c^2. (From Reference 32.)

The last issue I want to raise is the criteria we set for a strongly interacting gauge sector. Consider for definiteness the (I,J) = (2,0) partial wave, to be observed in the exotic W^+W^+ channel. To estimate the yield of W^+W^+ events in a strongly interacting gauge sector, many authors have extrapolated the threshold behavior (14) set by low-energy theorems up to the energy at which unitarity (in the form of $|a_{20}| < 1/2$) is saturated. Such a theory, which corresponds to $M_H \rightarrow \infty$ in the Lagrangian, is surely strongly interacting; but so is its counterpart with M_H = 4, or 2, or even 1 TeV/c^2. (I consider a theory in which $|a_{00}|$ = 1, or 1/2, strongly interacting.) As Figure 4 shows, the a_{20} partial-wave amplitude in a strongly interacting theory may be considerably smaller than extrapolation of the low-energy theorem would suggest, and the yield of W^+W^+ events will be correspondingly smaller. A large value of $|a_{20}|$ is therefore not an infallible diagnostic of a strongly interacting theory: it is sufficient, but not necessary. We should aspire to a comprehensive study of the (0,0), (1,1), and (2,0) partial waves.

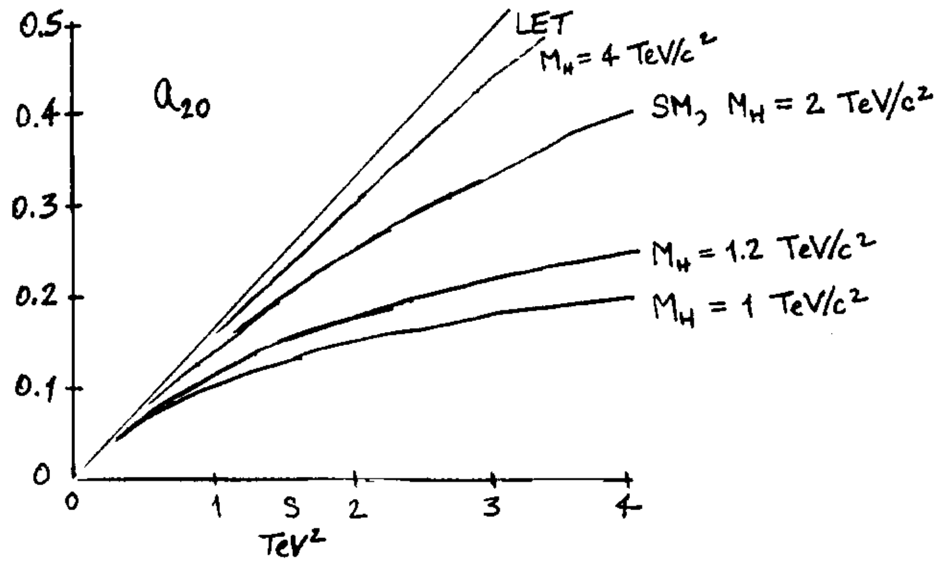

Figure 4. Lowest-order contribution to the $(I,J) = (2,0)$ partial-wave amplitude in the standard model, for various values of the Higgs-boson mass in the Lagrangian.

6. Conclusions

To examine the consequences of models for a strongly interacting gauge sector, it seems to me better to use the models themselves—suitably unitarized—than to rely on effective Lagrangians. Chiral perturbation theory, though flexible, is susceptible to the same dependence on unitarization procedure as fully specified models, and begins with far less information. We still need a credible method for solving a theory with a strongly coupled Higgs sector.

7. Acknowledgments

It is a pleasure to join in wishing the University of Oklahoma and Oklahoma State University a glorious second century, and to hope that the distinction and vitality of their physics programs will continue to grow. I thank our hosts, particularly Kim Milton and Mark Samuel, for warm hospitality in the Sooner State.

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