Effective field theories and the low-energy limit of strong interactions

Howard Georgi

Harvard

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PHENOMENOLOGICAL LAGRANGIANS

STEVEN WEINBERG

Lyman Laboratory of Physics, Harvard University

and

Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138, USA

“Introduction: A reminiscence

Julian Schwinger’s ideas have strongly influenced my understanding of phenomenological Lagrangians since 1966, when I made a visit to Harvard. At that time, I was trying to construct a **phenomenological Lagrangian** which would allow one to obtain the predictions of current algebra for soft pion matrix elements with less work, and with more insight into possible corrections. It was necessary to arrange that **the pion couplings in the Lagrangian would all be derivative interactions**, to suppress the incalculable graphs in which soft pions would be emitted from internal lines of a hard-particle process.”

“The mathematical approach I followed at first was quite clumsy; I started with the old σ model, in which the pion is in a chiral quartet with a 0+ isoscalar σ; then performed a space-time dependent chiral rotation which transformed $\{\pi, \sigma\}$ everywhere into $\{0, \sigma'\}$ with $\sigma = (\sigma^2 + \pi^2)^{1/2}$; and then re-introduced the pion field as the chiral rotation ‘angle’. The Lagrangian obtained in this way had a complicated and unfamiliar non-linear structure, but it did have the desired property of derivative coupling, because any space-time independent part of the rotation ‘angle’ would correspond to a symmetry of the theory, and so would not contribute to the Lagrangian.”

DYNAMICAL APPROACH TO CURRENT ALGEBRA

Steven Weinberg*
Department of Physics, University of California, Berkeley, California
(Received 12 December 1966)

An effective Lagrangian for soft-pion interactions is constructed such that lowest order perturbation theory precisely reproduces the results of current algebra.

“Schwinger suggested to me that one might be able to construct a suitable phenomenological Lagrangian directly, by introducing a pion field which from the beginning would have the non-linear transformation property of chiral rotation angles, and then just obeying the dictates of chiral symmetry for such a pion field. Following this suggestion, I worked out a general theory of non-linear realizations of chiral SU(2)×SU(2), which was soon after generalized to arbitrary groups in elegant papers of Callan, Coleman, Wess, and Zumino, and has since been applied by many authors. The importance of the approach suggested by Schwinger has been not only that it saves the work involved in the transition from an ordinary linear representation like $\{\pi, \sigma\}$ to a non-linear realization, **but more important, that it makes clear that the interactions of other hadrons with soft pions does not in any way depend on the chiral transformation properties of whatever fields are associated with these hadrons, but only on their isospin.**”

Nonlinear Realizations of Chiral Symmetry*

STEVEN WEINBERG†

Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received 25 September 1967)

“This article is intended as a review - I doubt that any of the material presented here is entirely new. In particular, although I have not tried here to judge the extent to which the ideas described below overlap those of source theory, I would not be surprised to find that these are points which long ago appeared in Schwinger’s work. In that case, I hope that he will take this paper as a little work of translation into the Vulgate, offered as a birthday present to an old friend.”

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PHENOMENOLOGICAL LAGRANGIANS

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One central idea of the paper is "... a 'theorem, which as far as I know has never been proven, but which I cannot imagine could be wrong. The 'theorem says that although individual quantum field theories have of course a good deal of content, quantum field theory itself has no content beyond analyticity, unitarity, cluster decomposition, and symmetry. This can be put more precisely in the context of perturbation theory: if one writes down the most general possible Lagrangian, including all terms consistent with assumed symmetry principles, and then calculates matrix elements with this Lagrangian to any given order of perturbation theory, the result will simply be the most general possible S-matrix consistent with analyticity, perturbative unitarity, cluster decomposition and the assumed symmetry principles."

All this becomes of practical value in the calculation of matrix elements for pions of low energy.

⋮

The real virtue of the phenomenological Lagrangian approach described in the preceding section is not that it provides an alternative derivation of a known result, but that it allows us in a systematic way to calculate corrections to this result

⋮

What is noteworthy is that the coefficients of the logarithmic terms can be calculated in detail so easily, by a one-loop calculation using a suitable phenomenological Lagrangian.

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Effective field theory, past and future*

Steven Weinberg

Theory Group, Department of Physics, University of Texas, Austin, TX 78712, USA
weinberg@physics.utexas.edu

I reminisce about the early development of effective field theories of the strong interactions, comment briefly on some other applications of effective field theories, and then take up the idea that the Standard Model and General Relativity are the leading terms in an effective field theory. Finally, I cite recent calculations that suggest that the effective field theory of gravitation and matter is asymptotically safe.

1960 Nambu — spontaneously broken symmetry $\to$ massless pion explains the Goldberger-Treiman relation - uses Goldstone theorem but not the details of symmetry

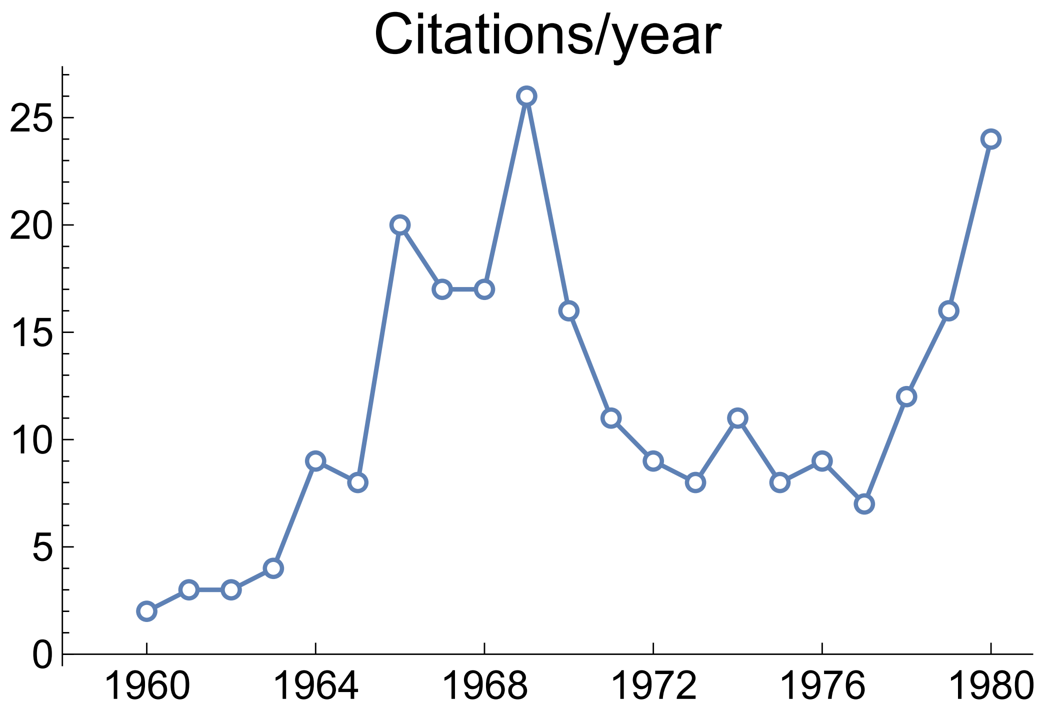
1964 commutation relations of SU(2)×SU(2) and SU(3)×SU(3) symmetry — Adler and Weisberger, K and Hyperon decays

1966 Weinberg — multiple πs from current algebra — $\pi\pi$ scattering — Lagrangian

1967 Weinberg and others — effective nonlinear chiral Lagrangian still justified by equivalence to current algebra — CCWZ

1967-1976 Standard model

Beginning in 1976 — changing attitude toward EFT — Erice talk on condensed matter physics — teaching QFT and explaining what it is and why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1960
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1980

Broken Symmetries*

JEFFREY GOLDSTONE
Trinity College, Cambridge University, Cambridge, England

AND

ABDUS SALAM AND STEVEN WEINBERG†
Imperial College of Science and Technology, London, England
(Received March 16, 1962)

Some proofs are presented of Goldstone's conjecture, that if there is continuous symmetry transformation under which the Lagrangian is invariant, then either the vacuum state is also invariant under the transformation, or there must exist spinless particles of zero mass.

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CURRENT-COMMUTATOR THEORY OF MULTIPLE PION PRODUCTION*

Steven Weinberg

Department of Physics, University of California, Berkeley, California

(Received 21 March 1966)

$$N_{fi}^{\mu_1\cdots\mu_n}(q_1\alpha_1,\cdots,q_n\alpha_n)$$

$$=M_{fi}^{\mu_1\cdots\mu_n}(q_1\alpha_1,\cdots,q_n\alpha_n+iF(q_1^{\mu_1}/q_1^2)M_{fi}^{\mu_2\cdots\mu_n}(q_2\alpha_2,\cdots,q_n\alpha_n;q_1\alpha_1)$$

$$+\text{permutations }-F^2(q_1^{\mu_1}q_2^{\mu_2}/q_1^2q_2^2)M_{fi}^{\mu_3\cdots\mu_n}(q_3\alpha_3\cdots q_n\alpha_n;q_1\alpha_1,q_2\alpha_2)$$

$$+\text{permutations}+\cdots+(iF)^n(q_1^{\mu_1}q_2^{\mu_2}\cdots q_n^{\mu_n}/q_1^2q_2^2\cdots q_n^2)M_{fi}(q_1\alpha_1,\cdots,q_n\alpha_n). \tag{4}$$

Multiplying by $(iF)^{-n}q_{1\mu_1}\cdots q_{n\mu_n}$, we find for the pion-emission matrix element

$$M_{fi}(q_1\alpha_1,\cdots,q_n\alpha_n)=G_{fi}(q_1\alpha_1,\cdots,q_n\alpha_n)+C_{fi}(q_1\alpha_1,\cdots,q_n\alpha_n), \tag{5}$$

where

$$G_{fi}(q_1\alpha_1,\cdots,q_n\alpha_n)\equiv(iF)^{-n}q_{1\mu_1}\cdots q_{n\mu_n}N_{fi}^{\mu_1\cdots\mu_n}(q_1\alpha_1,\cdots,q_n\alpha_n), \tag{6}$$

$$C_{fi}(q_1\alpha_1,\cdots,q_n\alpha_n)\equiv-(iF)^{-n}q_{1\mu_1}\cdots q_{n\mu_n}M_{fi}^{\mu_1\cdots\mu_n}(q_1\alpha_1,\cdots,q_n\alpha_n)$$

$$-(iF)^{-n+1}q_{2\mu_2}\cdots q_{n\mu_n}M_{fi}^{\mu_2\cdots\mu_n}(q_2\alpha_2\cdots q_n\alpha_n;q_1\alpha_1)+\text{permutations}$$

$$-(iF)^{-n+2}q_{3\mu_3}\cdots q_{n\mu_n}M_{fi}^{\mu_3\cdots\mu_n}(q_3\alpha_3\cdots q_n\alpha_n;q_1\alpha_1,q_2\alpha_2)+\text{permutations}$$

$$+\cdots+(iF)^{-1}q_{n\mu_n}M_{fi}^{\mu_n}(q_n\alpha_n;q_1\alpha_1,\cdots,q_{n-1}\alpha_{n-1}). \tag{7}$$

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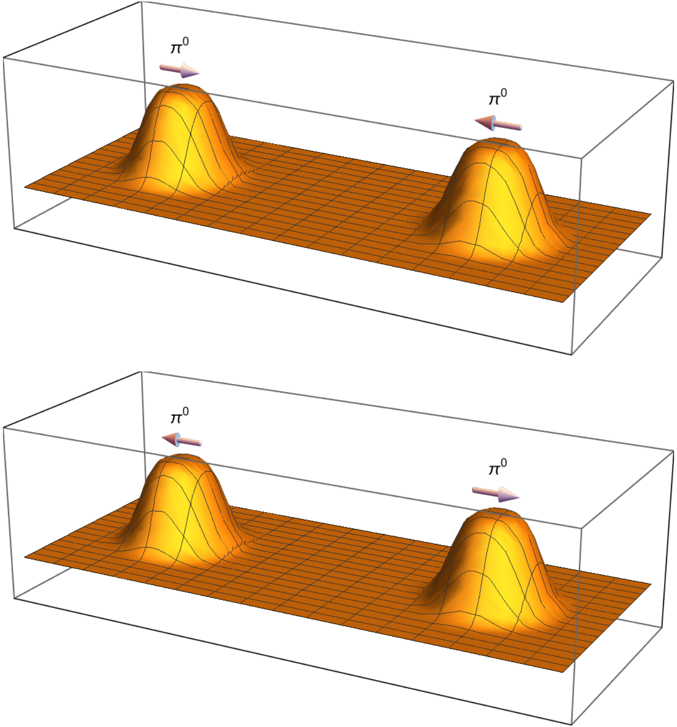
PION SCATTERING LENGTHS*

Steven Weinberg
Department of Physics, University of California, Berkeley, California
(Received 20 June 1966)



π^0
π^0
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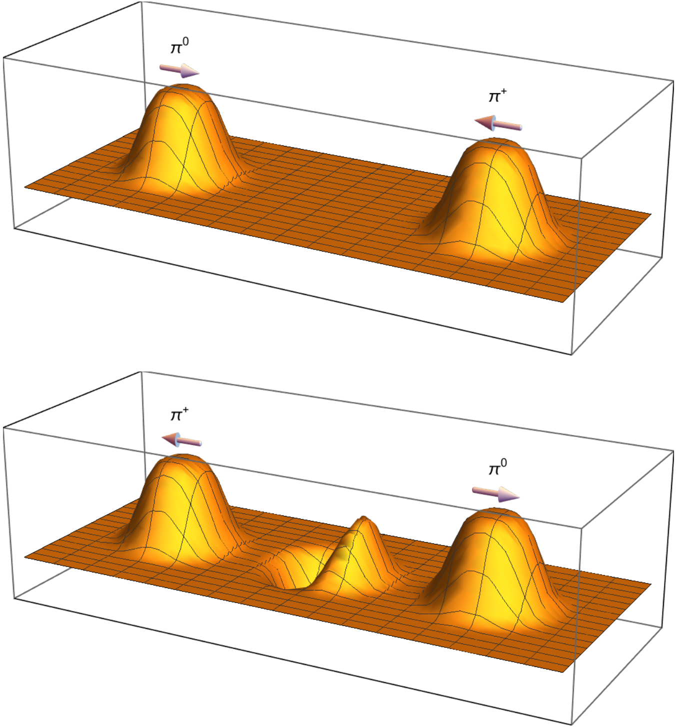
π^0



π0
π+
π+
π0

DYNAMICAL APPROACH TO CURRENT ALGEBRA

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Nonlinear Realizations of Chiral Symmetry*

STEVEN WEINBERG†
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 25 September 1967)

"We explore possible realizations of chiral symmetry, based on isotopic multiplets of fields whose transformation rules involve only isotopic-spin matrices and the pion field."

"The cumbersome operator techniques and weak interaction orientation of current algebra are replaced by a non-operator method based on strong interaction phenomenology."

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1964 commutation relations of SU(2)×SU(2) and SU(3)×SU(3) symmetry — Adler and Weisberger, K and Hyperon decays

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A MODEL OF LEPTONS*

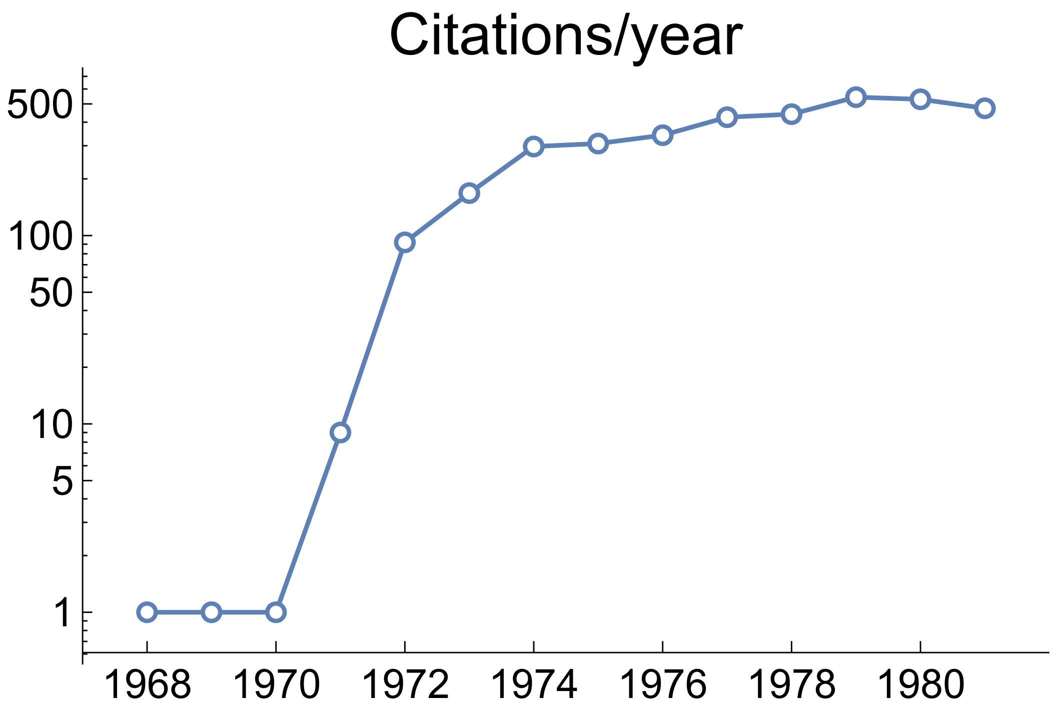
Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the

and on a right-handed singlet

$$R \equiv [\tfrac{1}{2}(1-\gamma_5)]e. \tag{2}$$

The largest group that leaves invariant the kinematic terms $-\bar{L}\gamma^{\mu}\partial_{\mu}L-\bar{R}\gamma^{\mu}\partial_{\mu}R$ of the Lagrangian consists of the electronic isospin $\vec{T}$ acting on L, plus the numbers N_L, N_R of left- and right-handed electron-type leptons. As far as we know, two of these symmetries are en-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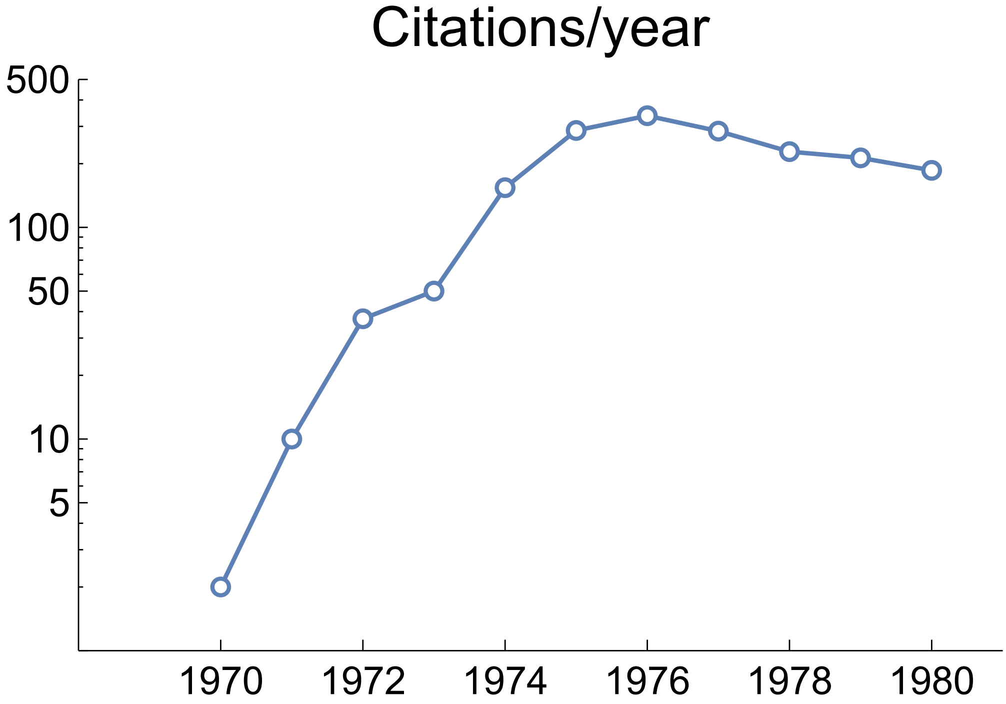
the GIM mechanism — brilliant prediction of the c quark Glashow, Illiopoulos and Maiani — justifying the early guess by Shelly and BJ — critical for the success of the standard model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Nuclear Physics B35 (1971) 167–188. North-Holland Publishing Company

RENORMALIZABLE LAGRANGIANS FOR MASSIVE YANG-MILLS FIELDS

G.'t HOOFT
Institute for Theoretical Physics, University of Utrecht

Received 13 July 1971

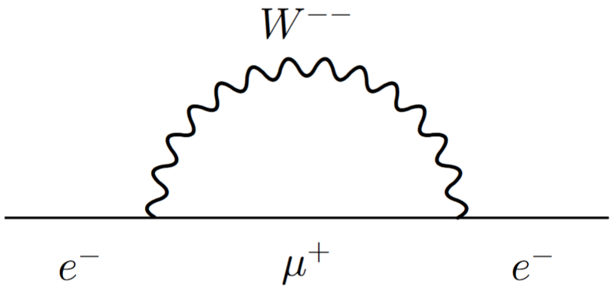
Abstract: Renormalizable models are constructed in which local gauge invariance is broken spontaneously. Feynman rules and Ward identities can be found by means of a path integral method, and they can be checked by algebra. In one of these models, which is studied in more detail, local SU(2) is broken in such a way that local U(1) remains as a symmetry. A renormalizable and unitary theory results, with photons, charged massive vector particles, and additional neutral scalar particles. It has three independent parameters.

Bj's relation

$$\frac{m_e}{m_\mu} \approx \frac{3\alpha}{\pi} \ln 2$$

$SU(3) \times SU(3)$ transforming under the respective $SU(3)$s as

$$\begin{pmatrix} \nu_e \\ e^- \\ \mu^+ \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\mu \\ \mu^- \\ e^+ \end{pmatrix}_L$$



$$\begin{pmatrix} \nu_e \\ e^- \\ \mu^+ \end{pmatrix}_L \qquad \begin{pmatrix} \nu_e \\ \mu^- \\ e^+ \end{pmatrix}_L$$

$$\langle\phi\rangle = \begin{pmatrix} u & 0 & 0 \\ 0 & u & 0 \\ 0 & 0 & -2u \end{pmatrix} \quad \text{breaks} \quad SU(3) \to SU(2) \times U(1)$$

$$Q = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}, \quad T_3 = \begin{pmatrix} \frac{1}{2} & 0 & 0 \\ 0 & -\frac{1}{2} & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad \sin^2\theta_W = \frac{\mathrm{Tr}\, T_3^2}{\mathrm{Tr}\, Q^2} = \frac{1/2}{2} = \frac{1}{4}$$

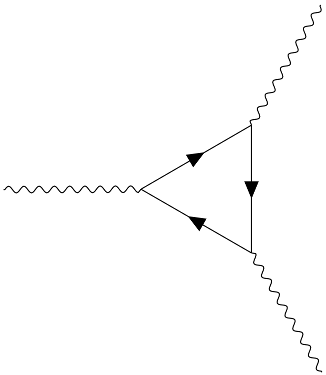
Renormalizability and "Accidental" Symmetry

Approximate Symmetries and Pseudo-Goldstone Bosons*

Steven Weinberg
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 27 October 1972)

In theories with spontaneously broken local symmetries, renormalizability sometimes forces the scalar field interactions to have a larger group of symmetries than the gauge field interactions. Symmetries can then arise in zeroth order which are violated by finite higher-order effects, thus providing a possible natural explanation of the approximate symmetries observed in nature. Such theories contain spinless bosons which behave like Goldstone bosons, but which pick up a small mass from higher-order effects.

Anomalies — Bouchiat, Iliopoulos, Meyer — Gross Jackiw



$$
\begin{array}{c}
SU(2) \\ \text{doublets}
\end{array}
\left\{
\overbrace{\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L}^{U(1)=-1/2}
\quad
\underbrace{\overbrace{\begin{pmatrix} u \\ \cos\theta\, d + \sin\theta\, s \end{pmatrix}_L \quad \begin{pmatrix} c \\ \cos\theta\, s - \sin\theta\, d \end{pmatrix}_L}^{U(1)=-1/6}}_{\text{3 colors — spectroscopy and anomalies}}
\right.
$$

$$
\begin{array}{c}
SU(2) \\ \text{singlets}
\end{array}
\left\{
\overbrace{e_R^- \quad \mu_R^-}^{U(1)=-1}
\quad
\underbrace{\overbrace{u_R \quad c_R}^{U(1)=2/3} \quad \overbrace{d_R \quad s_R}^{U(1)=-1/3}}_{\text{3 colors}}
\right.
$$

Dimensional transmutation and asymptotic freedom

Radiative Corrections as the Origin of Spontaneous Symmetry Breaking*

Sidney Coleman
and
Erick Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 8 November 1972)

Reliable Perturbative Results for Strong Interactions?*

H. David Politzer
Jefferson Physical Laboratories, Harvard University, Cambridge, Massachusetts 02138
(Received 3 May 1973)

Ultraviolet Behavior of Non-Abelian Gauge Theories*

David J. Gross† and Frank Wilczek
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 27 April 1973)

Current Algebra and Gauge Theories. II. Non-Abelian Gluons*

Steven Weinberg
Harvard University, Lyman Laboratory of Physics, Cambridge, Massachusetts 02138

(Received 27 August 1973)

The considerations of the first paper in this series are extended to non-Abelian gauge models of the strong, weak, and electromagnetic interactions. It is shown that for a large class of such theories, the strong interactions naturally conserve parity and strangeness, and possibly isospin and other quantum numbers as well. The corrections of second order in gauge couplings to such natural symmetries are convergent. In addition to the ordinary photon-exchange term, these corrections include other terms of order α, which take the form of shifts in the effective quark mass matrix, and which automatically conserve parity and strangeness. In theories with free-field asymptotic behavior, these order-α mass shifts may be correctly calculated ignoring all effects of the strong interactions. It is suggested that in such theories, the strong gauge group is not broken, and that the infrared divergences associated with the massless vector gluons prevent the production of quarks or gluons in collisions of ordinary hadrons.

However, when an attempt is made to remove a quark or gluon, the effective coupling $g(\kappa)$ must be taken with $1/\kappa$ of the order of the distance that the quark or gluon has traveled away from its fellows, so that the binding force would become increasingly large the further away any quark or gluon were pulled. In this picture, premature scaling works well because $g(\kappa)$ not only approaches zero as $\kappa \to \infty$, but it is not very large even at a few GeV.

Pati-Salam $SU(2)_L \times SU(2)_R \times SU(4)$

lepton number as a 4th color Left↔Right symmetry

Quark
Liberation
Front

$$SU(2)_L \left\{ \overbrace{\begin{pmatrix} u_{rL} & u_{gL} & u_{bL} & \nu_L \\ d_{rL} & d_{gL} & d_{bL} & e^-_L \end{pmatrix}}^{SU(4)} \right.$$

$$SU(2)_R \left\{ \overbrace{\begin{pmatrix} u_{rR} & u_{gR} & u_{bR} & \nu_R \\ d_{rR} & d_{gR} & d_{bR} & e^-_R \end{pmatrix}}^{SU(4)} \right.$$

Pati-Salam $SU(2) \times SU(2) \times SU(4)$ model with IR slavery

$$SU(2)_R \left\{ \overbrace{\begin{pmatrix} u_{rR} & u_{gR} & u_{bR} & \nu_R \\ d_{rR} & d_{gR} & d_{bR} & e^-_R \end{pmatrix}}^{SU(4)} \right.$$

Scalar field with same properties and a VEV

$$SU(2)_R \left\{ \overbrace{\begin{pmatrix} u_{rR} & u_{gR} & u_{bR} & \boxed{\nu_R} \\ d_{rR} & d_{gR} & d_{bR} & e^-_R \end{pmatrix}}^{SU(4)} \right.$$

Could also couple to a sterile ν to get rid of ν_R

$$SU(4) \approx SO(6) \qquad SU(2) \times SU(2) \approx SO(4) \qquad 4 + 6 = 10$$

$SO(10):$

$$\vec{\sigma}/2\,, \quad \vec{\tau}/2\,, \quad \vec{\eta}/2\,,$$

$$\vec{\sigma}\,\alpha_1/2\,, \quad \vec{\tau}\,\alpha_2/2\,, \quad \vec{\eta}\,\alpha_3/2\,,$$

$$\vec{\sigma}\,\vec{\tau}\,\alpha_3/2\,, \quad \vec{\tau}\,\vec{\eta}\,\alpha_1/2\,, \quad \vec{\eta}\,\vec{\sigma}\,\alpha_2/2$$

with the $SU(2)\times SU(2)\times SU(4)$ embedded as follows:

$SU(2)_L:$ $\quad \vec{\eta}\,(1+\alpha_3)/4$

$SU(2)_R:$ $\quad \vec{\eta}\,(1-\alpha_3)/4$

$SU(4):$ $\quad \vec{\sigma}/2\,,\ \vec{\tau}/2\,,\ \vec{\sigma}\,\vec{\tau}\,\alpha_3/2$

$$\begin{pmatrix} \nu \\ u_r \\ u_g \\ u_b \\ e^- \\ d_r \\ d_g \\ d_b \\ \bar{d}_b \\ \bar{d}_g \\ \bar{d}_r \\ e^+ \\ \bar{u}_b \\ \bar{u}_g \\ \bar{u}_r \\ \bar{\nu} \end{pmatrix} \quad \begin{matrix} \left.\begin{matrix} \\ \\ \\ \\ \\ \\ \\ \\ \end{matrix}\right\} (2_L, 1, 4) \\ \left.\begin{matrix} \\ \\ \\ \\ \\ \\ \\ \\ \end{matrix}\right\} (1, 2_R, \bar{4}) \end{matrix}$$

$SU(5)$

$$24 = 5^2 - 1 \qquad 3 + 2 = 5!!!! \qquad \mathbf{5} = (3,1)_{-1/3} + (1,2)_{1/2}$$

$$\begin{aligned} \mathbf{10} &= \mathbf{5} \times \mathbf{5}_A \\ &= \left[(3,1)_{-1/3} + (1,2)_{1/2}\right] \times \left[(3,1)_{-1/3} + (1,2)_{1/2}\right]_A \\ &= (\overline{3},1)_{-2/3} + (3,2)_{1/6} + (1,1)_1 \end{aligned}$$

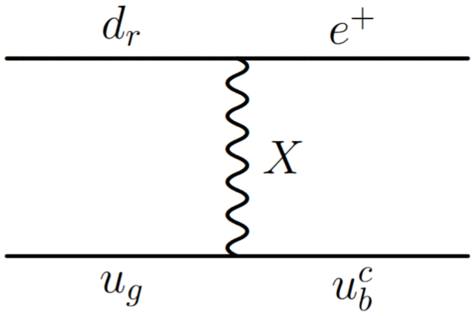
$\mathbf{16}$ of $SO(10)$ was $\mathbf{10} + \overline{\mathbf{5}} + \mathbf{1}$.

$$\langle 24 \rangle \propto \begin{pmatrix} 3 & 0 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 & 0 \\ 0 & 0 & -2 & 0 & 0 \\ 0 & 0 & 0 & -2 & 0 \\ 0 & 0 & 0 & 0 & -2 \end{pmatrix}$$

$$\mathbf{5} = (3,1)_{-1/3} + (1,2)_{1/2} \Rightarrow \sin^2\theta = \frac{\mathrm{Tr}\, T_3^2}{\mathrm{Tr}\, Q^2} = \frac{2 \times 1/4}{3 \times 1/9 + 1 + 0} = 3/8\,.$$

quarks and leptons masses with a **5** of scalars the masses had an $SU(4)$ symmetry $\Rightarrow$ the masses of the charge $-1/3$ quarks would be the same as that of the corresponding charged leptons — we now know that this doesn't work, but at the time $m_\mu = m_s$ didn't seem crazy at all

SO(10), SU(5), Proton decay and Huge scales



It was clear that this would cause the proton decay, $p \to e^+\pi^0$

Unification of couplings

HG, Quinn, Weinberg

- Continuum EFT

versus

Wilsonian

- Matching

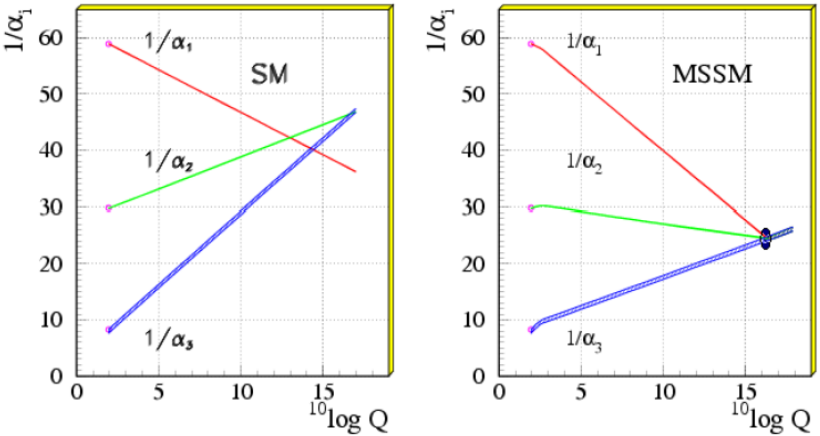
versus

“integrating out”

- Subtraction

versus

renormalization



from the PDG

Hierarchy of Interactions in Unified Gauge Theories*

H. Georgi,† H. R. Quinn, and S. Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 15 May 1974)

We present a general formalism for calculating the renormalization effects which make strong interactions strong in simple gauge theories of strong, electromagnetic, and weak interactions. In an SU(5) model the superheavy gauge bosons arising in the spontaneous breakdown to observed interactions have mass perhaps as large as 10^{17} GeV, almost the Planck mass. Mixing-angle predictions are substantially modified.

New Approach to the Renormalization Group*

Steven Weinberg
Harvard University, Lyman Laboratory of Physics, Cambridge, Massachusetts 02138
(Received 13 August 1973)

A new set of renormalization-group equations is presented. These equations are based on a renormalization procedure in which counterterms are calculated for zero unrenormalized mass. Unlike the Gell-Mann–Low and Callan-Symanzik equations, they can be solved for arbitrary momenta. The solutions involve a momentum-dependent effective mass as well as a momentum-dependent effective coupling constant. By studying these solutions at large momenta, it can be shown that the nonleading terms discarded by previous authors do, in fact, remain negligible when the perturbation series is summed to all orders if, and only if, the effective mass vanishes at large momentum, which will be the case if a certain anomalous dimension is less than unity, as it is in asymptotically free theories. In this case, the new renormalization-group equations can be used at large momentum to derive not only the leading term, but the first three terms in an asymptotic expansion of any Green's function. These results are also applied to Wilson coefficient functions, and an important cancellation of anomalous dimensions is noted.

Infrared singularities and massive fields*

Thomas Appelquist[†] and J. Carazzone[‡]
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 30 September 1974)

We examine some problems associated with the low-momentum behavior of gauge theories and other renormalizable field theories. Our main interest is in the infrared structure of unbroken non-Abelian gauge theories and how this is affected by the presence of other heavy fields coupled to the massless gauge fields. It is shown in the context of a simple model of gauge mesons coupled to massive fermions that the heavy fields decouple at low momenta except for their contribution to renormalization effects. This result is used to discuss the mass-shell structure of the fermion propagator. The decoupling theorem is then stated for a general renormalizable theory and applied to some interesting examples. One is a more general gauge theory which makes use of the Higgs mechanism and attempts to unify the elementary particle forces. Another is the connection of the linear and nonlinear σ models in the limit $m_\sigma \longrightarrow \infty$.

Now let us see how to take renormalization effects into account. The gauge couplings are functions of the momentum scale μ, and the above relations among gauge couplings really only apply when μ is much larger than the superheavy boson masses, where the breaking of G may be neglected. However, the observed values of the gauge couplings refer to much smaller values of μ, of the order of the W and Z masses, or even smaller. The problem is to bridge the gap between superlarge values of μ, where G imposes relations among the gauge couplings, and ordinary values of μ, where the gauge couplings are observed.

In order to accomplish this, we make use of the theorem[8] that all matrix elements involving only "ordinary" external particles with momenta and masses much less than all superheavy masses may be calculated in an effective renormalizable field theory, which is just the original field theory with all superheavy particles omitted, but with coupling constants that may depend on the superheavy masses. All other effects of the superheavy particles are suppressed by factors of an ordinary mass divided by a superheavy mass.

QCD and heavy quarks

Rare decay modes of the *K* mesons in gauge theories

M. K. Gaillard* and Benjamin W. Lee†
National Accelerator Laboratory, Batavia, Illinois 60510‡
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Heavy Quarks and e^+e^- Annihilation*

Thomas Appelquist† and H. David Politzer‡
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
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The effects of new, heavy quarks are examined in a colored quark-gluon model. The e^+e^- total cross section scales for energies far above any quark mass. However, it is much greater than the scaling prediction in a domain about the nominal two-heavy-quark threshold, despite $\sigma_{e^+e^-}$ being a weak-coupling problem above 2 GeV. We expect spikes at the low end of this domain and a broad enhancement at the upper end.

•Are the New Particles Baryon-Antibaryon Nuclei? Alfred S. Goldhaber and Maurice Goldhaber Phys. Rev. Lett. 34, 36 (1975) — Published 6 January 1975

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•Possible Explanation of the New Resonance in e+e- Annihilation S. Borchardt, V. S. Mathur, and S. Okubo Phys. Rev. Lett. 34, 38 (1975) — Published 6 January 1975

•Model with Three Charmed Quarks R. Michael Barnett Phys. Rev. Lett. 34, 41 (1975) — Published 6 January 1975

•Heavy Quarks and e+e- Annihilation Thomas Appelquist and H. David Politzer Phys. Rev. Lett. 34, 43 (1975) — Published 6 January 1975

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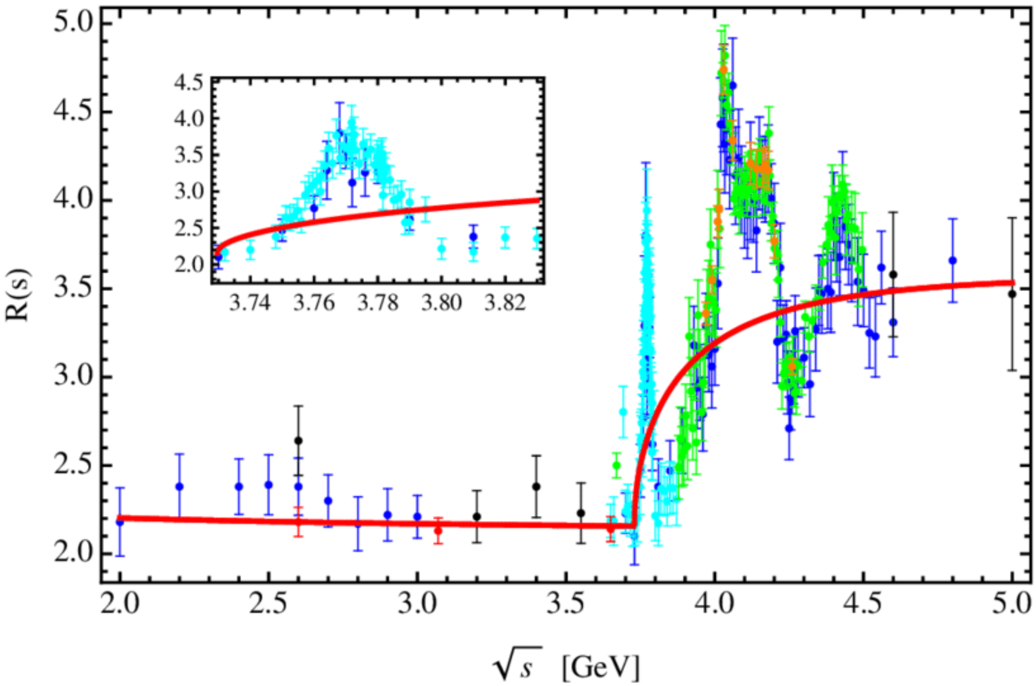

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SHORT DISTANCE ANALYSIS OF WEAK INTERACTIONS *

Edward WITTEN **

Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540

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We systematically formulate the short distance analysis of weak interactions, and show that in an asymptotically free theory one can calculate the dependence of any weak amplitude on the W boson and heavy quark masses. Our main purpose is to settle some conceptual questions, but we also derive some new quantitative results. For example, we show that in the SU(3) gauge theory with four quark triplets, the two W boson contribution to $K_L \to \mu\bar{\mu}$ will differ from the free quark theory estimate by a factor

$$25(1 - (\bar{\alpha}(M_W/\bar{\alpha}(m_{p'})^{1/25})\,(\bar{\alpha}(M_W)/\bar{\alpha}(m_{p'}))^{24/25} .$$

We also show that the amplitudes for $K^+ \to \pi^+ e^+ e^-$ will differ from the free quark theory estimate by a factor of

$$1.66(\bar{\alpha}(M_W)/\bar{\alpha}(m_{p'}))^{2/9} - 1.88(\bar{\alpha}(M_W)/\bar{\alpha}(m_{p'})^{-4/9} .$$

The U(1) problem*

Steven Weinberg

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

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A detailed analysis of the problems associated with the conserved U(1) axial-vector current in quark-gluon models is presented. It is shown that such models involve a light isoscalar pseudoscalar boson, with a mass less than $\sqrt{3}\, m_\pi$. The existence of this boson would produce a strong off-shell variation in the $\eta \to 3\pi$ matrix element, thus invalidating the usual conclusions about the rate and energy dependence of this decay. Following Kogut and Susskind, it is proposed that the light Goldstone boson is actually a dipole, with positive- and negative-metric parts, which cancel in matrix elements of gluon-gauge-invariant operators but not in operators such as the U(1) current. It is shown that the masses of the observable pseudoscalar bosons and the η decay rate are then just as they would be in a theory without the U(1) symmetry, and in fair agreement with experiment. The application of current algebra to theories with charmed quarks is briefly discussed.

Symmetry Breaking through Bell-Jackiw Anomalies*

G. 't Hooft†

Department of Physics, Harvard University, Cambridge, Massachusetts 02138

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In models of fermions coupled to gauge fields certain current-conservation laws are violated by Bell-Jackiw anomalies. In perturbation theory the total charge corresponding to such currents seems to be still conserved, but here it is shown that nonperturbative effects can give rise to interactions that violate the charge conservation. One consequence is baryon and lepton number nonconservation in $V-A$ gauge theories with charm. Another is the nonvanishing mass squared of the η.

After "Phenomenological Lagrangians"

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Chiral Perturbation Theory to One Loop*

J. GASSER

Institut für Theoretische Physik der Universität Bern, 3012 Bern, Switzerland

AND

H. LEUTWYLER†

CERN, Geneva, Switzerland

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Large N Chiral Dynamics ● Renormalization and Effective Lagrangians ● Chiral Quarks and the Nonrelativistic Quark Model ● Chiral Perturbation Theory to One Loop ● Volume Dependence of the Energy Spectrum in Massive Quantum Field Theories. 1. Stable Particle States ● Light Quarks at Low Temperatures ● Light Pseudoscalars, Particle Physics and Cosmology ● Nucleons with Chiral Loops ● Nonlinear Realization and Hidden Local Symmetries ● The Cosmological Constant Problem ● Chiral Lagrangians for Massive Spin 1 Fields ● Nuclear forces from chiral Lagrangians ● Baryon chiral perturbation theory using a heavy fermion Lagrangian ● Union of chiral and heavy quark symmetries ● Chiral structure of the nucleon ● QCD phenomenology based on a chiral effective Lagrangian ● General relativity as an effective field theory: The leading quantum corrections ● Chiral dynamics in nucleons and nuclei ● The Spectrum of the nucleons and the strange hyperons and chiral dynamics ● The Two nucleon potential from chiral Lagrangians ● Recent progress in quantum hadrodynamics ● N/D description of two meson amplitudes and chiral symmetry ● Summing Sudakov logarithms in B —> X(s gamma) in effective field theory ● $\pi\pi$ scattering ● Electroweak symmetry breaking from dimensional deconstruction ● Effective field theory for few nucleon systems ● Hidden local symmetry at loop: A New perspective of composite gauge boson and chiral phase transition ● Accurate charge dependent nucleon nucleon potential at fourth order of chiral perturbation theory ● TeV symmetry and the little hierarchy problem ● Chiral effective model with the Polyakov loop ● Little hierarchy, little Higgses, and a little symmetry ● Modern Theory of Nuclear Forces ● The Muon g-2 ● Chiral effective field theory and nuclear forces ● Ab initio no core shell model.