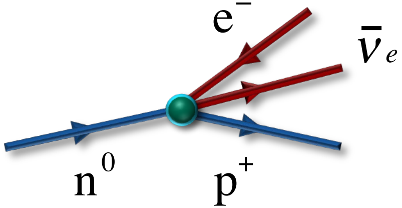
Higgs: The Untold Story

SERGIO F. NOVAES

SPRACE, Unesp

Electroweak Interaction Before the SM (1)



Quantum Electrodynamics (QED)

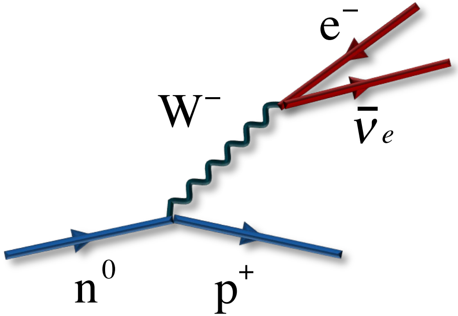
- Foundations established by Dirac in 1927
- Astonishing agreement with the experimental results
  - The best theory we have!
- Became a prototype for the construction of new model

Weak Interactions

- Fermi proposes the first field theory description of the beta decay in 1934
  - Employs the neutrino recently proposed by Pauli
  - Loosely inspired by QED

$$L = \frac{G_F}{\sqrt{2}}\left(\bar{\psi}_p \gamma_\mu \psi_n\right)\left(\bar{\psi}_e \gamma^\mu \psi_\nu\right)$$

- Schwinger (1957): Interaction is transmitted by a IVB:
  - Charged: charge-changing currents.
  - Very massive: short range



Electroweak Interaction Before the SM (2)

Became quite successful after some improvements:

- (V – A) structure (Lee & Yang, Wu, Feynman & Gell-Mann)
- Strangeness (Cabibbo)
- Quark model (Gell-Mann & Zweig)

Describes very-well the low energy phenomena

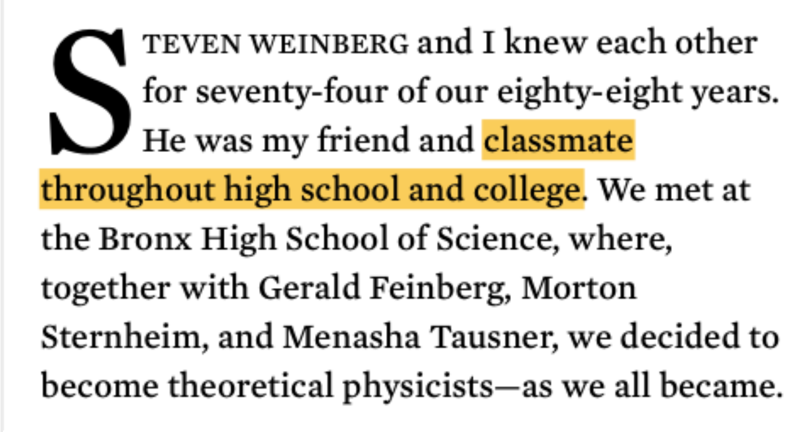
- However, the theory violates unitarity for E ~ 500 GeV
- Theory becomes inconsistent

Several attempts to construct a consistent model:

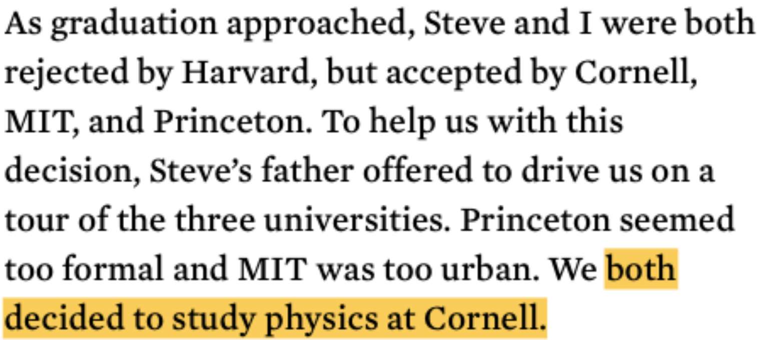
- Glashow (1961):
  - Describe weak and electromagnetic interactions in a unified way
  - First introduction of the neutral intermediate weak boson Z^0
  - The vector boson mass was introduced by hand
    - Theory was **not** renormalizable!

Sheldon Lee Glashow

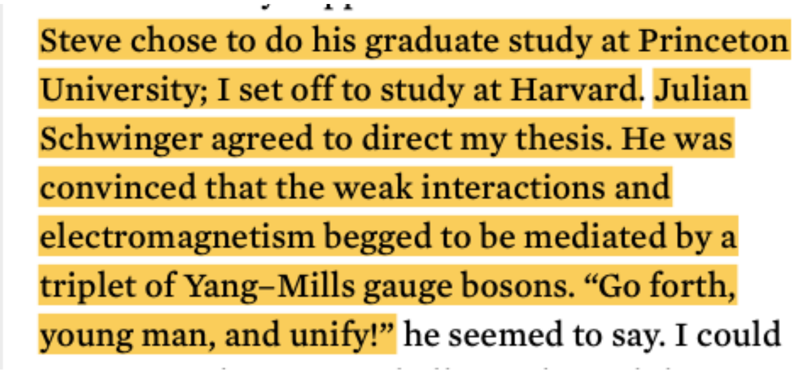
In Memoriam: Steven Weinberg



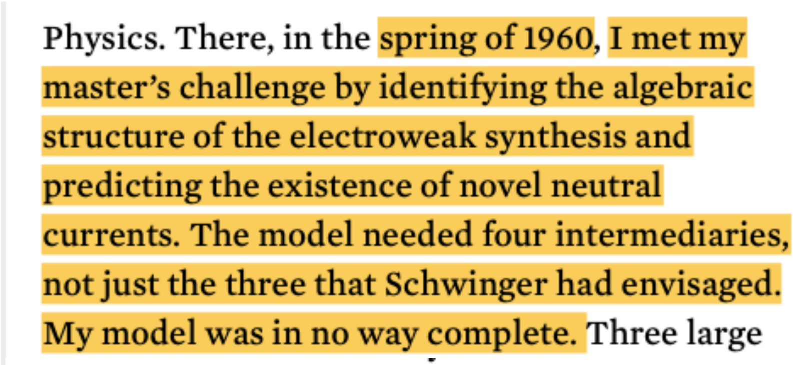
STEVEN WEINBERG and I knew each other for seventy-four of our eighty-eight years. He was my friend and classmate throughout high school and college. We met at the Bronx High School of Science, where, together with Gerald Feinberg, Morton Sternheim, and Menasha Tausner, we decided to become theoretical physicists—as we all became.



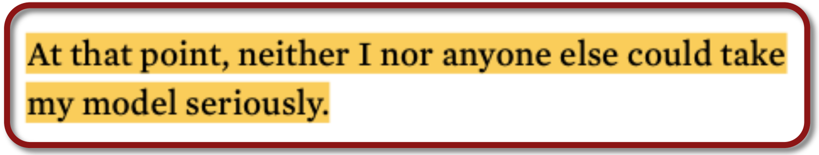
As graduation approached, Steve and I were both rejected by Harvard, but accepted by Cornell, MIT, and Princeton. To help us with this decision, Steve's father offered to drive us on a tour of the three universities. Princeton seemed too formal and MIT was too urban. We both decided to study physics at Cornell.



Steve chose to do his graduate study at Princeton University; I set off to study at Harvard. Julian Schwinger agreed to direct my thesis. He was convinced that the weak interactions and electromagnetism begged to be mediated by a triplet of Yang–Mills gauge bosons. "Go forth, young man, and unify!" he seemed to say. I could

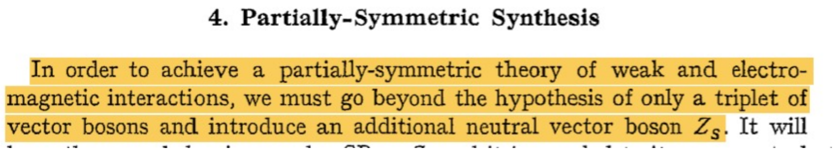


Physics. There, in the spring of 1960, I met my master's challenge by identifying the algebraic structure of the electroweak synthesis and predicting the existence of novel neutral currents. The model needed four intermediaries, not just the three that Schwinger had envisaged. My model was in no way complete. Three large



At that point, neither I nor anyone else could take my model seriously.

https://inference-review.com/article/in-memoriam-steven-weinberg



4. Partially-Symmetric Synthesis

In order to achieve a partially-symmetric theory of weak and electromagnetic interactions, we must go beyond the hypothesis of only a triplet of vector bosons and introduce an additional neutral vector boson Z_S. It will

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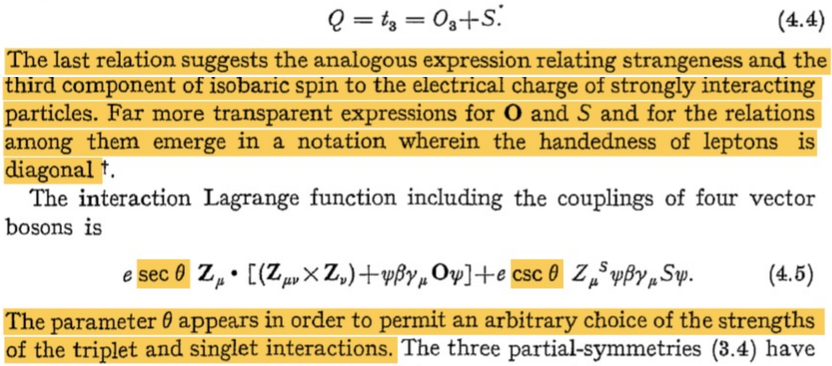


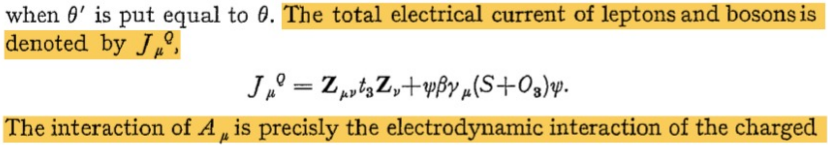
$$Q = t_3 = O_3 + S. \qquad (4.4)$$

The last relation suggests the analogous expression relating strangeness and the third component of isobaric spin to the electrical charge of strongly interacting particles. Far more transparent expressions for **O** and S and for the relations among them emerge in a notation wherein the handedness of leptons is diagonal †.

The interaction Lagrange function including the couplings of four vector bosons is

$$e \sec\theta\, \mathbf{Z}_\mu \cdot [(\mathbf{Z}_{\mu\nu} \times \mathbf{Z}_\nu) + \psi\beta\gamma_\mu \mathbf{O}\psi] + e \csc\theta\, Z_\mu^S \psi\beta\gamma_\mu S\psi. \qquad (4.5)$$

The parameter θ appears in order to permit an arbitrary choice of the strengths of the triplet and singlet interactions. The three partial-symmetries (3.4) have

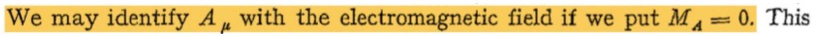


when θ' is put equal to θ. The total electrical current of leptons and bosons is denoted by J_μ^Q,

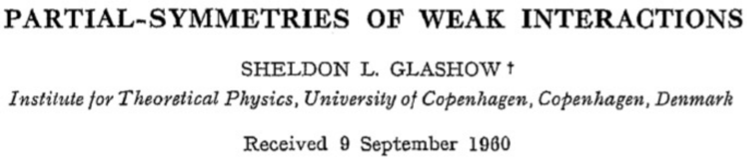
$$J_\mu^Q = \mathbf{Z}_{\mu\nu} t_3 \mathbf{Z}_\nu + \psi\beta\gamma_\mu (S + O_3)\psi.$$

The interaction of A_μ is precisely the electrodynamic interaction of the charged

…



We may identify A_μ with the electromagnetic field if we put $M_A = 0$. This

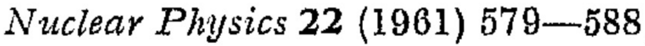


PARTIAL-SYMMETRIES OF WEAK INTERACTIONS

SHELDON L. GLASHOW †
Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark

Received 9 September 1960

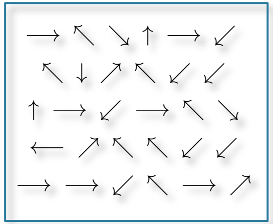
- ❑ Describe weak and EM interactions in a unified way
- ❑ First introduction of the neutral intermediate weak boson Z^0
- ❑ Defines a misture of O_3 (**A_3**) e S (**B**) via the “Weinberg angle” (θ_W)
- ❑ *Three large questions remained:*
  - ▪ *How did the weak interaction intermediaries acquire their mass?*
  - ▪ *Could the model describe nuclear particles as well as leptons?*
  - ▪ *Was the theory renormalizable and hence mathematically consistent?*

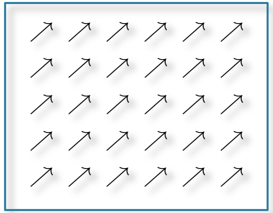


Nuclear Physics **22** (1961) 579—588

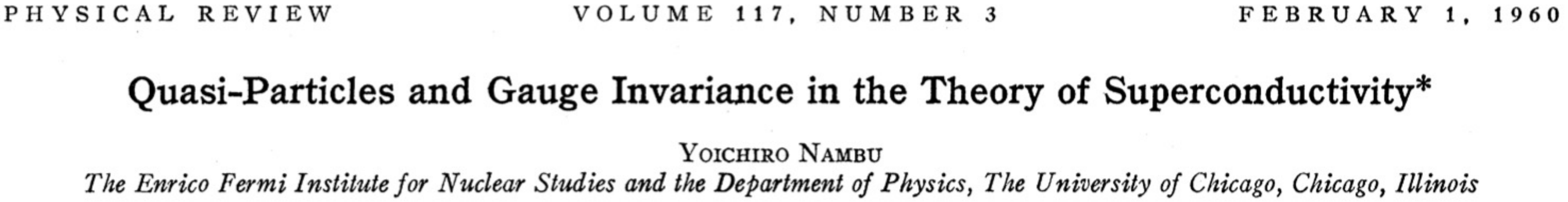
On the Spontaneous Symmetry Breaking

- ☐ The SSB occurs in a uniform medium consisting of a large number of elements.
  - Ferromagnetic materials:
    - ○ Above the Curie temperature is spatially invariant: magnetization = 0
    - ○ Below the Curie temperature magnetization acquires a constant nonvanishing value point in a certain direction.
      The residual rotational symmetries, which leave the orientation of this vector invariant, remain unbroken.
  - Crystals:
    - ○ Periodic arrays of atoms that are not invariant under all translations
    - ○ Invariant only under a small subset of translations by a lattice vector





physical system	broken symmetry	massless bosons
ferromagnets	rotational invariance	spin waves
crystals	translational invariance	phonons



PHYSICAL REVIEW VOLUME 117, NUMBER 3 FEBRUARY 1, 1960

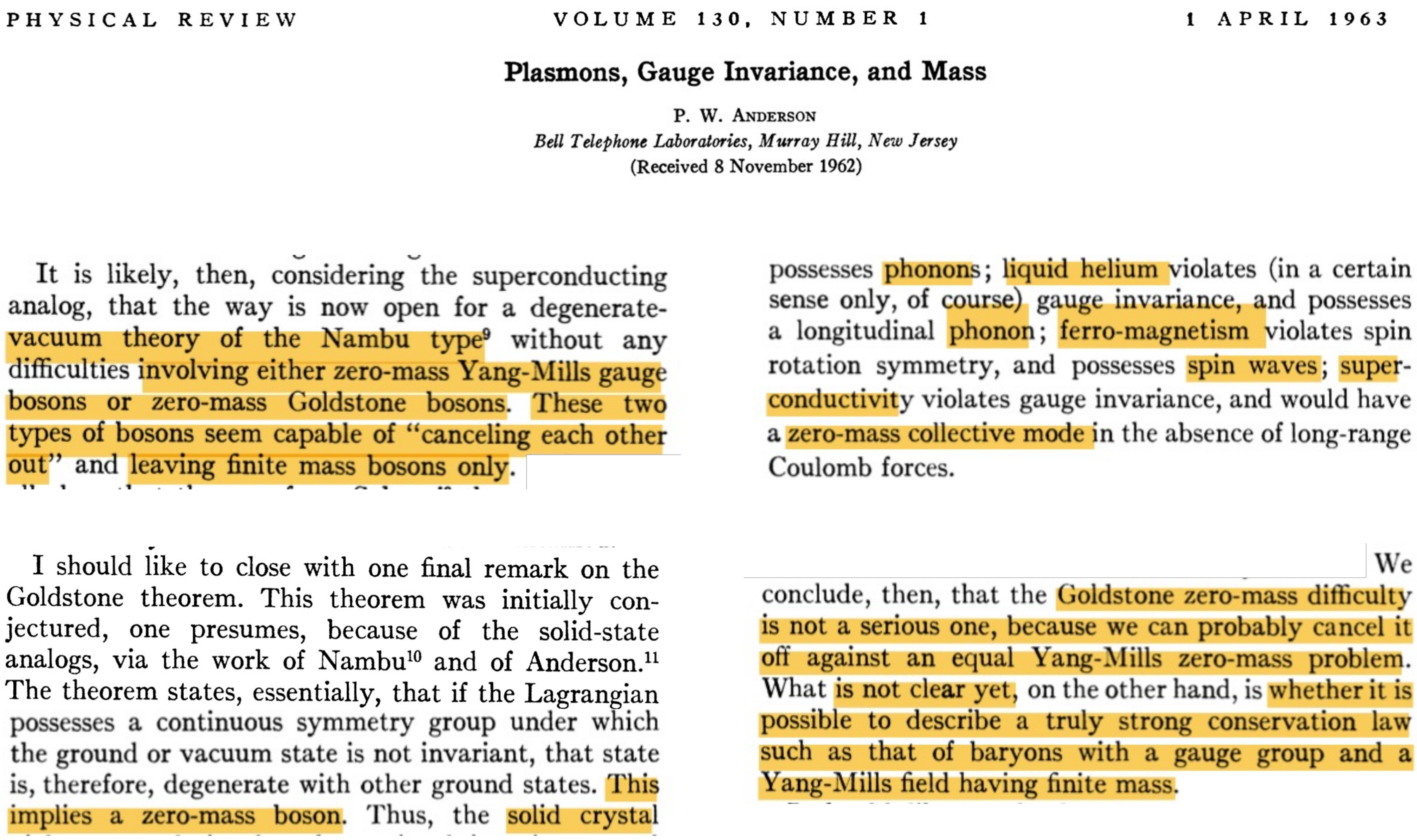
Quasi-Particles and Gauge Invariance in the Theory of Superconductivity*

YOICHIRO NAMBU

The Enrico Fermi Institute for Nuclear Studies and the Department of Physics, The University of Chicago, Chicago, Illinois

- The formal similarity of the Bogoliubov-Valatin equation to the Dirac equation naturally led me to transport the BCS theory to particle physics.
- The gap (BCS) goes over to the mass M, which breaks chirality γ_5 rather than the ordinary charge ~1.
- The axial current is the analog of the electromagnetic vector current in the BCS theory.
- So chiral symmetry is compatible with a finite nucleon mass M provided that there exists a massless pseudoscalar NG boson. There is a pseudoscalar pion, and the vector and axial vector interactions that appear in weak decays of the nucleons and the pion
- In view of the smallness of m_π compared to M, I made the hypothesis that the axial current is an approximately conserved quantity, the nucleon mass is generated by an SSB of chirality, and the pion is the corresponding NG boson which should become massless in the limit of exact conservation. Proton and neutron masses should also become equal.

REVIEWS OF MODERN PHYSICS, VOLUME 81, JULY–SEPTEMBER 2009



PHYSICAL REVIEW VOLUME 130, NUMBER 1 1 APRIL 1963

Plasmons, Gauge Invariance, and Mass

P. W. Anderson
Bell Telephone Laboratories, Murray Hill, New Jersey

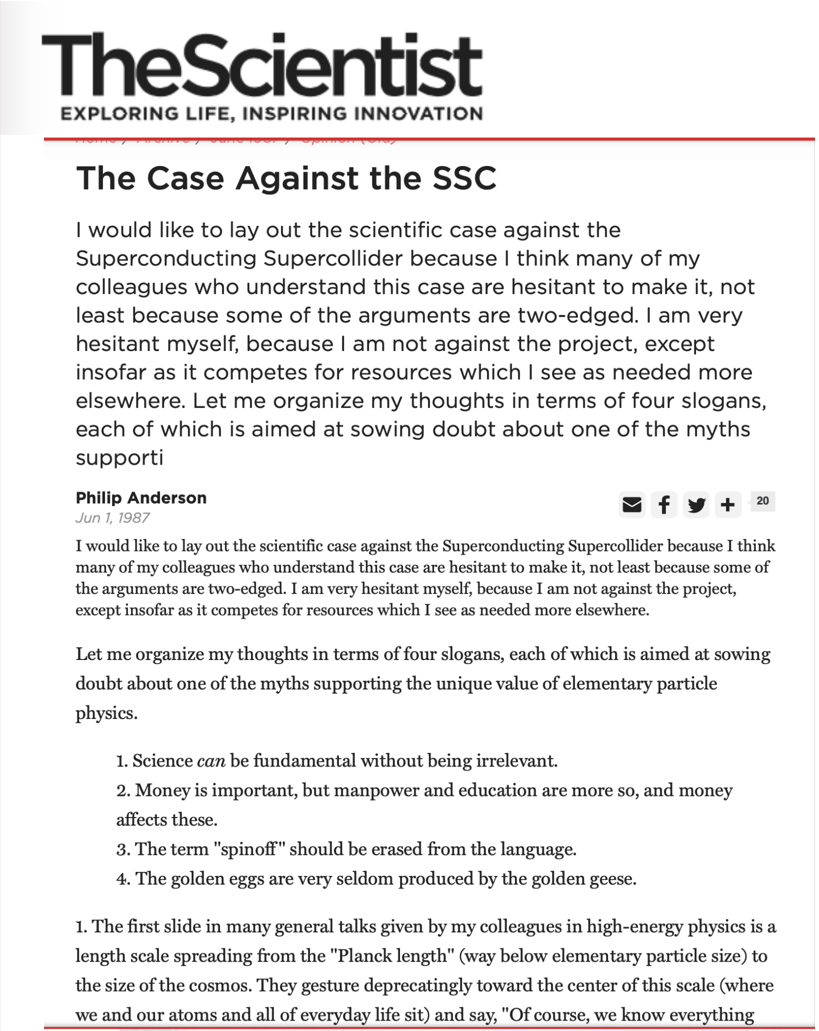
(Received 8 November 1962)

It is likely, then, considering the superconducting analog, that the way is now open for a degenerate-vacuum theory of the Nambu type[9] without any difficulties involving either zero-mass Yang-Mills gauge bosons or zero-mass Goldstone bosons. These two types of bosons seem capable of "canceling each other out" and leaving finite mass bosons only.

possesses phonons; liquid helium violates (in a certain sense only, of course) gauge invariance, and possesses a longitudinal phonon; ferro-magnetism violates spin rotation symmetry, and possesses spin waves; superconductivity violates gauge invariance, and would have a zero-mass collective mode in the absence of long-range Coulomb forces.

I should like to close with one final remark on the Goldstone theorem. This theorem was initially conjectured, one presumes, because of the solid-state analogs, via the work of Nambu[10] and of Anderson.[11] The theorem states, essentially, that if the Lagrangian possesses a continuous symmetry group under which the ground or vacuum state is not invariant, that state is, therefore, degenerate with other ground states. This implies a zero-mass boson. Thus, the solid crystal

We conclude, then, that the Goldstone zero-mass difficulty is not a serious one, because we can probably cancel it off against an equal Yang-Mills zero-mass problem. What is not clear yet, on the other hand, is whether it is possible to describe a truly strong conservation law such as that of baryons with a gauge group and a Yang-Mills field having finite mass.



TheScientist
EXPLORING LIFE, INSPIRING INNOVATION

The Case Against the SSC

I would like to lay out the scientific case against the Superconducting Supercollider because I think many of my colleagues who understand this case are hesitant to make it, not least because some of the arguments are two-edged. I am very hesitant myself, because I am not against the project, except insofar as it competes for resources which I see as needed more elsewhere. Let me organize my thoughts in terms of four slogans, each of which is aimed at sowing doubt about one of the myths supporti

Philip Anderson
Jun 1, 1987

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Let me organize my thoughts in terms of four slogans, each of which is aimed at sowing doubt about one of the myths supporting the unique value of elementary particle physics.

1. Science *can* be fundamental without being irrelevant.
2. Money is important, but manpower and education are more so, and money affects these.
3. The term "spinoff" should be erased from the language.
4. The golden eggs are very seldom produced by the golden geese.

1. The first slide in many general talks given by my colleagues in high-energy physics is a length scale spreading from the "Planck length" (way below elementary particle size) to the size of the cosmos. They gesture deprecatingly toward the center of this scale (where we and our atoms and all of everyday life sit) and say, "Of course, we know everything

The Goldstone Theorem

- When an exact continuous global symmetry is spontaneously broken, i.e., it is not a symmetry of the physical vacuum; the theory contains one massless scalar particle for each broken generator of the original symmetry group.

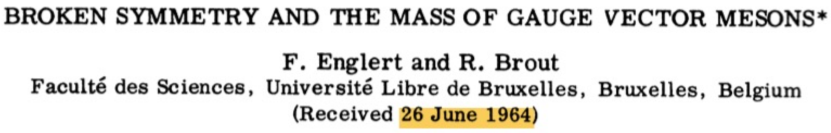
$$\begin{gathered} G(N) \rightarrow g(n) \\ \Downarrow \\ (N-n)\, GB \end{gathered}$$

- The unavoidable GB prevented the use of the SSB
- A solid field theory result
  - Proven by Goldstone, Salam, Weinberg (1961)
  - Rigorous algebraic proof by Kastler, Robinson and Swieca (1962).

Englert-Brout-Higgs-Guralnik-Hagen-Kibble Mechanism

A Field Theory with spontaneous symmetry breakdown,
without massless GB, and with massive vector boson

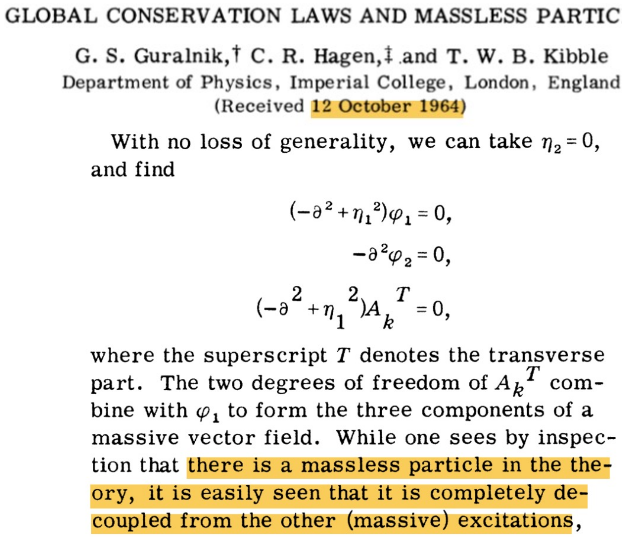
- F. Englert and R. Brout,
  - Phys. Rev. Lett.13, 321-323 (26/Jun/1964)
- P. W. Higgs,
  - Phys. Lett. 12, 132-133 (27/Jul/1964)
- Peter W. Higgs,
  - Phys. Rev. Lett.13, 508-509 (31/Aug/1964) [1st version rejected in PLB]
- G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble,
  - Phys. Rev. Lett. 13, 585-587 (12/Oct/1964)



BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

- Theories with degenerate vacuum (broken symmetry) have been the subject of intensive study since their inception by Nambu.
- A characteristic feature of such theories is the possible existence of zero-mass bosons which tend to restore the symmetry.
- We shall show that it is precisely these singularities which maintain the gauge invariance of the theory, despite the fact that the vector meson acquires mass.



GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

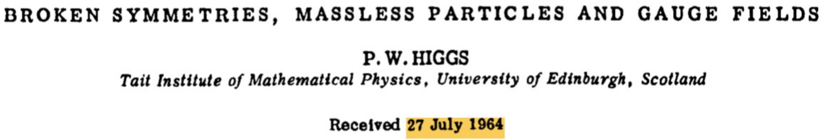
With no loss of generality, we can take $\eta_2=0$, and find

$$(-\partial^2+\eta_1^2)\varphi_1=0,$$

$$-\partial^2\varphi_2=0,$$

$$(-\partial^2+\eta_1^2)A_k^T=0,$$

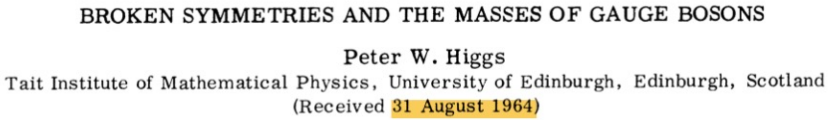
where the superscript T denotes the transverse part. The two degrees of freedom of A_k^T combine with φ_1 to form the three components of a massive vector field. While one sees by inspection that there is a massless particle in the theory, it is easily seen that it is completely decoupled from the other (massive) excitations,



BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964



BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
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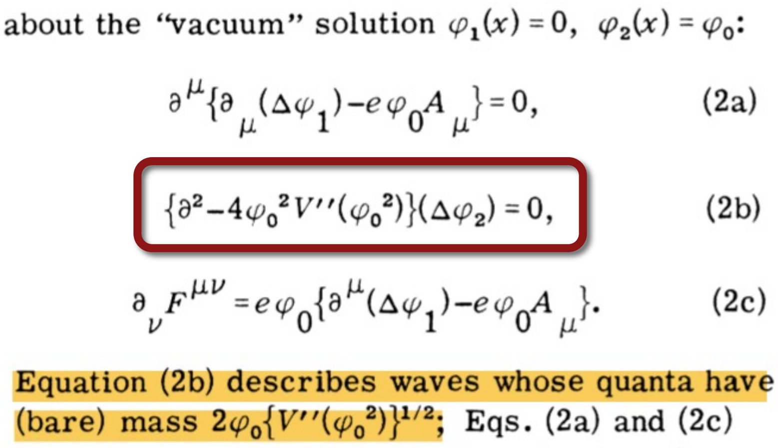
(Received 31 August 1964)



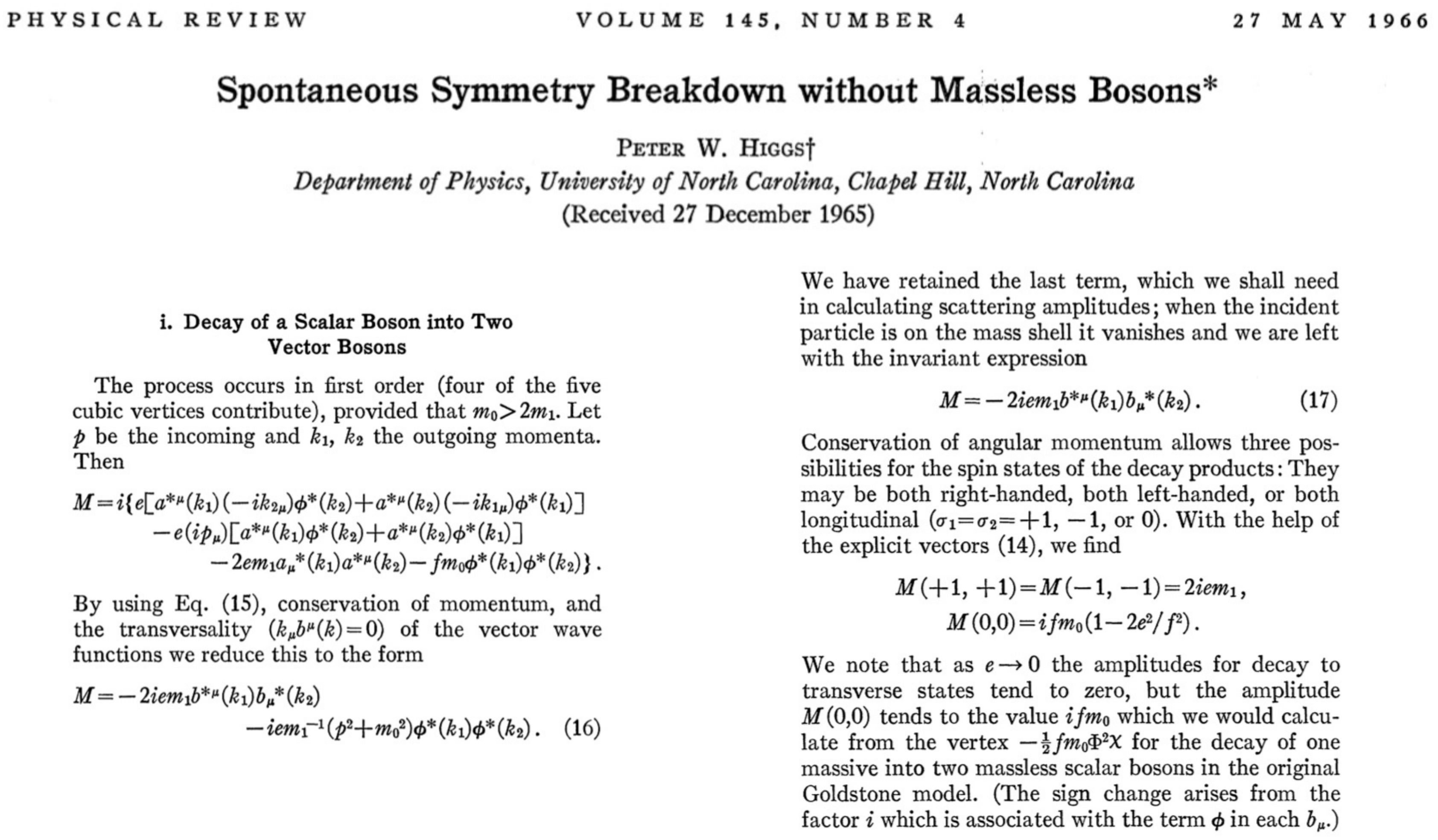
about the "vacuum" solution $\varphi_1(x)=0$, $\varphi_2(x)=\varphi_0$:

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1)-e\varphi_0A_\mu\}=0, \qquad (2a)$$

$$\boxed{\{\partial^2-4\varphi_0^2V''(\varphi_0^2)\}(\Delta\varphi_2)=0,} \qquad (2b)$$

$$\partial_\nu F^{\mu\nu}=e\varphi_0\{\partial^\mu(\Delta\varphi_1)-e\varphi_0A_\mu\}. \qquad (2c)$$

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0^2)\}^{1/2}$; Eqs. (2a) and (2c)



PHYSICAL REVIEW VOLUME 145, NUMBER 4 27 MAY 1966

Spontaneous Symmetry Breakdown without Massless Bosons[*]

PETER W. HIGGS[†]
Department of Physics, University of North Carolina, Chapel Hill, North Carolina
(Received 27 December 1965)

i. Decay of a Scalar Boson into Two Vector Bosons

The process occurs in first order (four of the five cubic vertices contribute), provided that $m_0 > 2m_1$. Let p be the incoming and k_1, k_2 the outgoing momenta. Then

$$M = i\{e[a^{*\mu}(k_1)(-ik_{2\mu})\phi^*(k_2) + a^{*\mu}(k_2)(-ik_{1\mu})\phi^*(k_1)] \\ - e(ip_\mu)[a^{*\mu}(k_1)\phi^*(k_2) + a^{*\mu}(k_2)\phi^*(k_1)] \\ - 2em_1 a_\mu^*(k_1)a^{*\mu}(k_2) - fm_0\phi^*(k_1)\phi^*(k_2)\}\,.$$

By using Eq. (15), conservation of momentum, and the transversality ($k_\mu b^\mu(k) = 0$) of the vector wave functions we reduce this to the form

$$M = -2iem_1 b^{*\mu}(k_1)b_\mu^*(k_2) \\ - iem_1^{-1}(p^2 + m_0^2)\phi^*(k_1)\phi^*(k_2)\,. \quad (16)$$

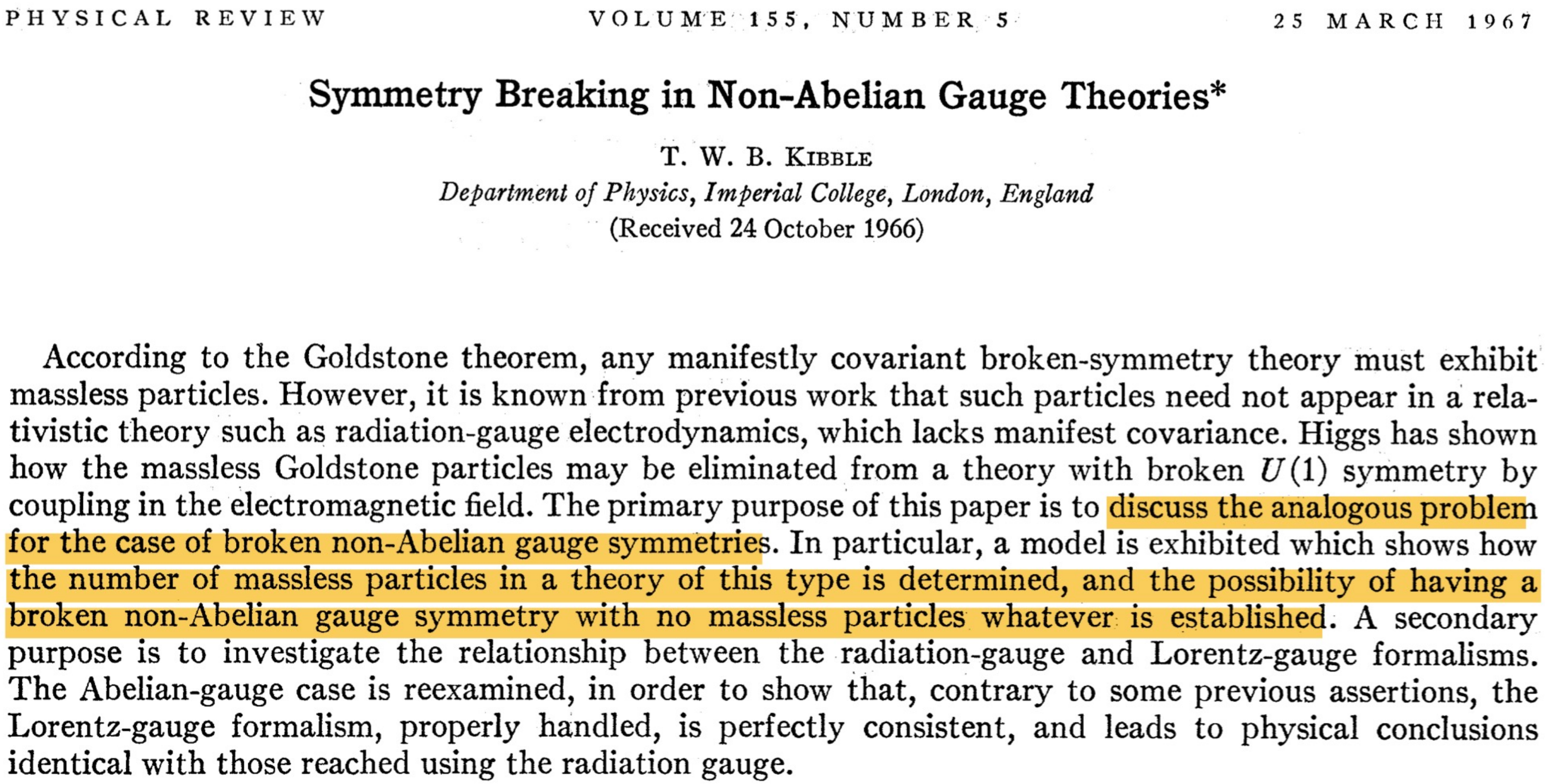
We have retained the last term, which we shall need in calculating scattering amplitudes; when the incident particle is on the mass shell it vanishes and we are left with the invariant expression

$$M = -2iem_1 b^{*\mu}(k_1)b_\mu^*(k_2)\,. \quad (17)$$

Conservation of angular momentum allows three possibilities for the spin states of the decay products: They may be both right-handed, both left-handed, or both longitudinal ($\sigma_1 = \sigma_2 = +1, -1$, or 0). With the help of the explicit vectors (14), we find

$$M(+1,+1) = M(-1,-1) = 2iem_1\,, \\ M(0,0) = ifm_0(1 - 2e^2/f^2)\,.$$

We note that as $e \rightarrow 0$ the amplitudes for decay to transverse states tend to zero, but the amplitude $M(0,0)$ tends to the value ifm_0 which we would calculate from the vertex $-\frac{1}{2}fm_0\Phi^2\chi$ for the decay of one massive into two massless scalar bosons in the original Goldstone model. (The sign change arises from the factor i which is associated with the term ϕ in each b_μ.)



PHYSICAL REVIEW VOLUME 155, NUMBER 5 25 MARCH 1967

Symmetry Breaking in Non-Abelian Gauge Theories*

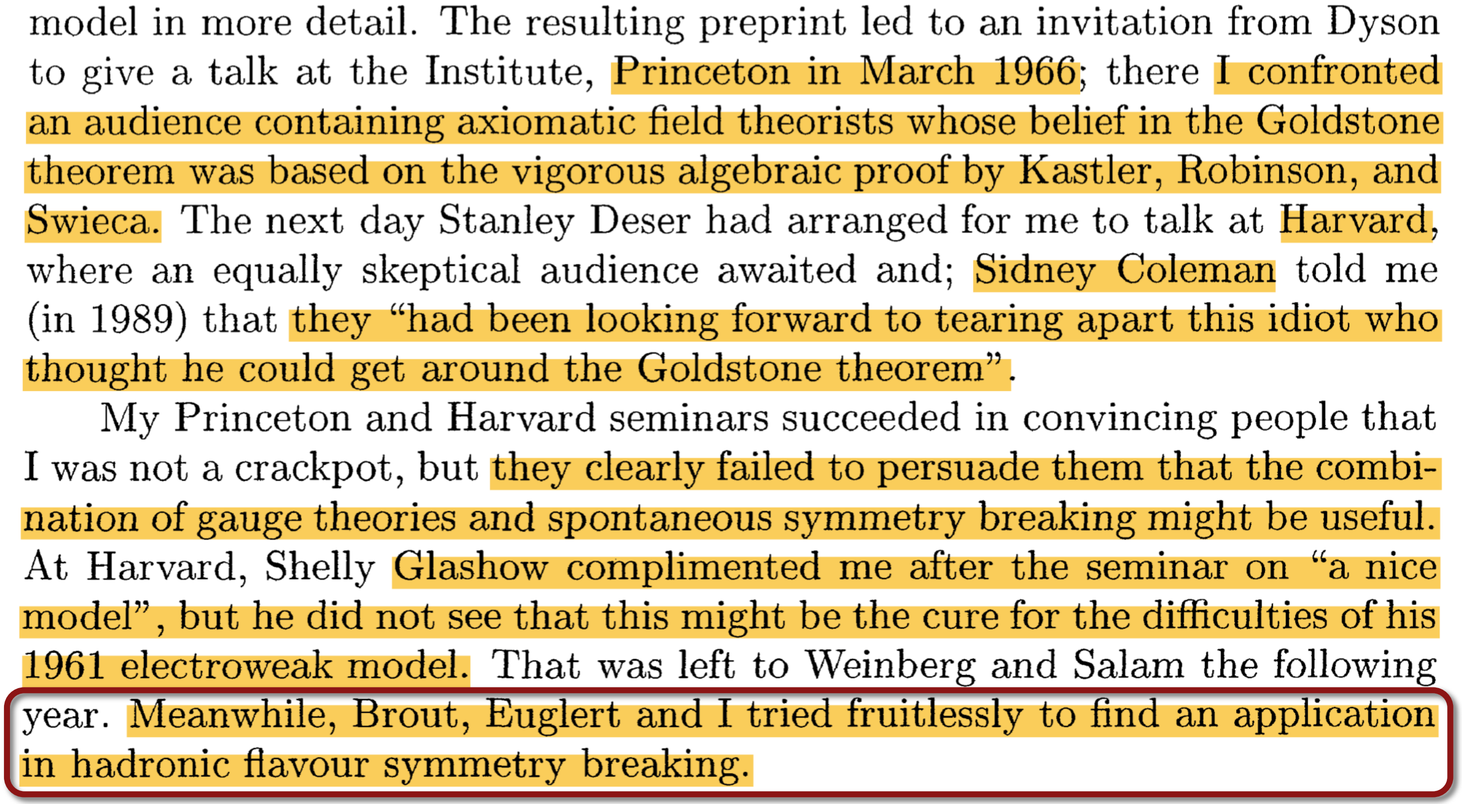
T. W. B. Kibble
Department of Physics, Imperial College, London, England

(Received 24 October 1966)

According to the Goldstone theorem, any manifestly covariant broken-symmetry theory must exhibit massless particles. However, it is known from previous work that such particles need not appear in a relativistic theory such as radiation-gauge electrodynamics, which lacks manifest covariance. Higgs has shown how the massless Goldstone particles may be eliminated from a theory with broken $U(1)$ symmetry by coupling in the electromagnetic field. The primary purpose of this paper is to discuss the analogous problem for the case of broken non-Abelian gauge symmetries. In particular, a model is exhibited which shows how the number of massless particles in a theory of this type is determined, and the possibility of having a broken non-Abelian gauge symmetry with no massless particles whatever is established. A secondary purpose is to investigate the relationship between the radiation-gauge and Lorentz-gauge formalisms. The Abelian-gauge case is reexamined, in order to show that, contrary to some previous assertions, the Lorentz-gauge formalism, properly handled, is perfectly consistent, and leads to physical conclusions identical with those reached using the radiation gauge.

MY LIFE AS A BOSON: THE STORY OF "THE HIGGS"

PETER HIGGS



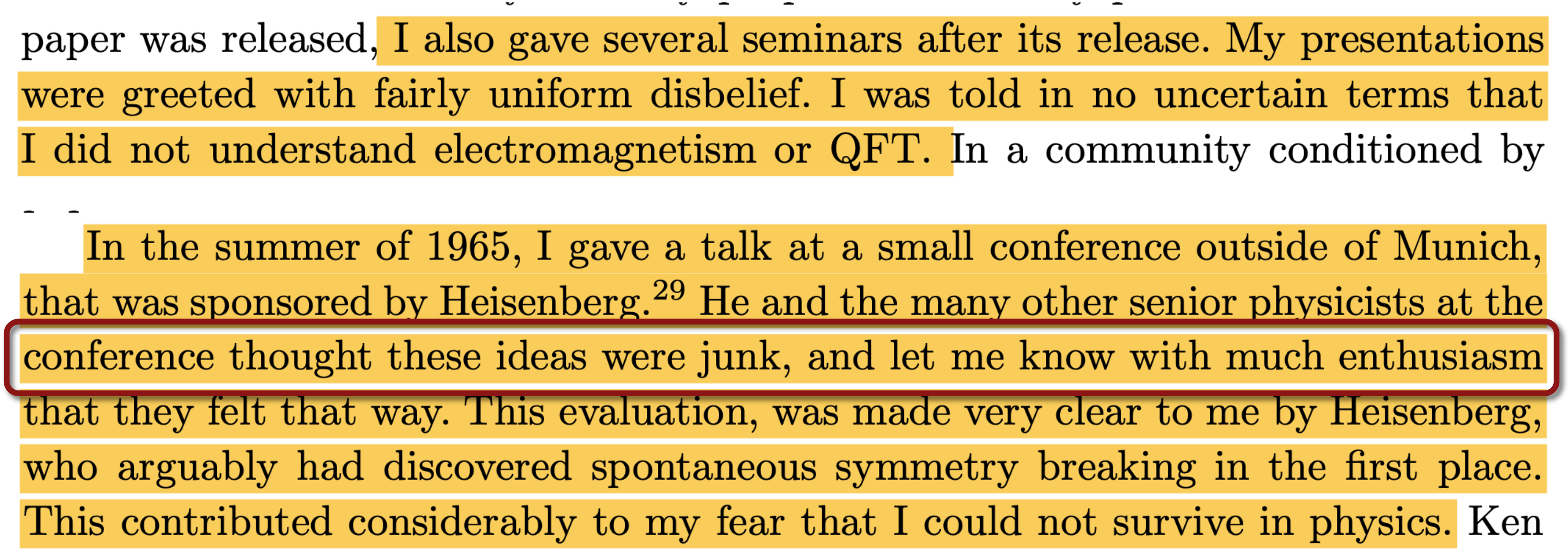
model in more detail. The resulting preprint led to an invitation from Dyson to give a talk at the Institute, Princeton in March 1966; there I confronted an audience containing axiomatic field theorists whose belief in the Goldstone theorem was based on the vigorous algebraic proof by Kastler, Robinson, and Swieca. The next day Stanley Deser had arranged for me to talk at Harvard, where an equally skeptical audience awaited and; Sidney Coleman told me (in 1989) that they "had been looking forward to tearing apart this idiot who thought he could get around the Goldstone theorem".

My Princeton and Harvard seminars succeeded in convincing people that I was not a crackpot, but they clearly failed to persuade them that the combination of gauge theories and spontaneous symmetry breaking might be useful. At Harvard, Shelly Glashow complimented me after the seminar on "a nice model", but he did not see that this might be the cure for the difficulties of his 1961 electroweak model. That was left to Weinberg and Salam the following year. Meanwhile, Brout, Euglert and I tried fruitlessly to find an application in hadronic flavour symmetry breaking.

International Journal of Modern Physics A Vol. 17, Suppl. (2002) 86–88

THE HISTORY OF THE GURALNIK, HAGEN AND KIBBLE DEVELOPMENT OF THE THEORY OF SPONTANEOUS SYMMETRY BREAKING AND GAUGE PARTICLES

GERALD S. GURALNIK



paper was released, I also gave several seminars after its release. My presentations were greeted with fairly uniform disbelief. I was told in no uncertain terms that I did not understand electromagnetism or QFT. In a community conditioned by

In the summer of 1965, I gave a talk at a small conference outside of Munich, that was sponsored by Heisenberg.[29] He and the many other senior physicists at the conference thought these ideas were junk, and let me know with much enthusiasm that they felt that way. This evaluation, was made very clear to me by Heisenberg, who arguably had discovered spontaneous symmetry breaking in the first place. This contributed considerably to my fear that I could not survive in physics. Ken

International Journal of Modern Physics A
Vol. 24, No. 14 (2009) 2601–2627

The Breakthrough: 2½ pages, 18,515 citations, 1 NP

VOLUME 19, NUMBER 21 PHYSICAL REVIEW LETTERS 20 NOVEMBER 1967

[11] In obtaining the expression (11) the mass difference between the charged and neutral has been ignored.

[12] M. Ademollo and R. Gatto, Nuovo Cimento 44A, 282 (1966); see also J. Pasupathy and R. E. Marshak, Phys. Rev. Letters 17, 888 (1966).

[13] The predicted ratio [eq. (12)] from the current algebra is slightly larger than that (0.23%) obtained from the ρ-dominance model of Ref. 2. This seems to be true also in the other case of the ratio $\Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\gamma\gamma)$ calculated in Refs. 12 and 14.

[14] L. M. Brown and P. Singer, Phys. Rev. Letters 8, 460 (1962).

A MODEL OF LEPTONS*

Steven Weinberg†
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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 weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the specter of unwanted massless Goldstone bosons.[2] This note will describe a model in which the symmetry between the electromagnetic and weak interactions is spontaneously broken, but in which the Goldstone bosons are avoided by introducing the photon and the intermediate-boson fields as gauge fields.[3] The model may be renormalizable.

We will restrict our attention to symmetry groups that connect the observed electron-type leptons only with each other, i.e., not with muon-type leptons or other unobserved leptons or hadrons. The symmetries then act on a left-handed doublet

$$L \equiv [\tfrac{1}{2}(1+\gamma_5)]\begin{pmatrix} \nu_e \\ e \end{pmatrix} \qquad (1)$$

and on a right-handed singlet

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

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 entirely unbroken: the charge $Q = T_3 - N_R - \tfrac{1}{2}N_L$, and the electron number $N = N_R + N_L$. But the gauge field corresponding to an unbroken symmetry will have zero mass,[4] and there is no massless particle coupled to N,[5] so we must form our gauge group out of the electronic isospin $\vec{T}$ and the electronic hyperchange $Y \equiv N_R + \tfrac{1}{2}N_L$.

Therefore, we shall construct our Lagrangian out of L and R, plus gauge fields $\vec{A}_\mu$ and B_μ coupled to $\vec{T}$ and Y, plus a spin-zero doublet

$$\varphi = \begin{pmatrix} \varphi^0 \\ \varphi^- \end{pmatrix} \qquad (3)$$

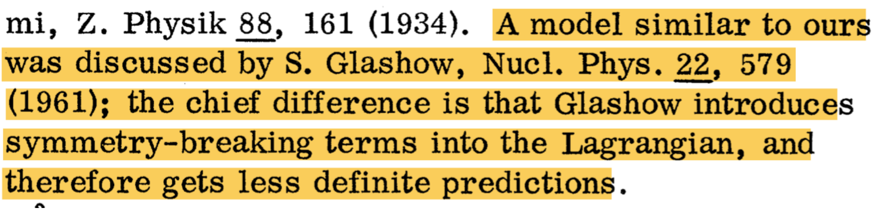
whose vacuum expectation value will break $\vec{T}$ and Y and give the electron its mass. The only renormalizable Lagrangian which is invariant under $\vec{T}$ and Y gauge transformations is

$$\mathfrak{L} = -\tfrac{1}{4}(\partial_\mu\vec{A}_\nu - \partial_\nu\vec{A}_\mu + g\vec{A}_\mu\times\vec{A}_\nu)^2 - \tfrac{1}{4}(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 - \bar{R}\gamma^\mu(\partial_\mu - ig'B_\mu)R - L\gamma^\mu(\partial_\mu ig\vec{t}\cdot\vec{A}_\mu - i\tfrac{1}{2}g'B_\mu)L$$

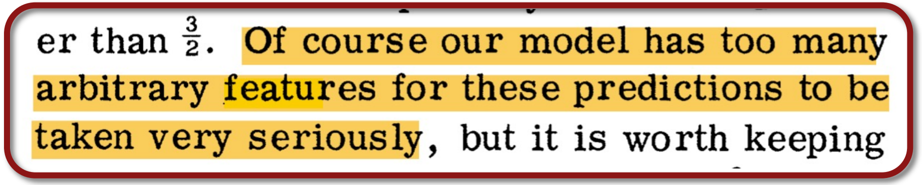
$$-\tfrac{1}{2}|\partial_\mu\varphi - ig\vec{A}_\mu\cdot\vec{t}\varphi + i\tfrac{1}{2}g'B_\mu\varphi|^2 - G_e(\bar{L}\varphi R + \bar{R}\varphi^\dagger L) - M_1{}^2\varphi^\dagger\varphi + h(\varphi^\dagger\varphi)^2. \qquad (4)$$

We have chosen the phase of the R field to make G_e real, and can also adjust the phase of the L and Q fields to make the vacuum expectation value $\lambda \equiv \langle\varphi^0\rangle$ real. The "physical" φ fields are then φ^-

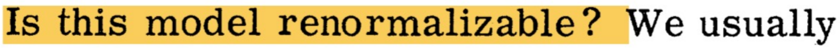
1264



mi, Z. Physik 88, 161 (1934). A model similar to ours was discussed by S. Glashow, Nucl. Phys. 22, 579 (1961); the chief difference is that Glashow introduces symmetry-breaking terms into the Lagrangian, and therefore gets less definite predictions.

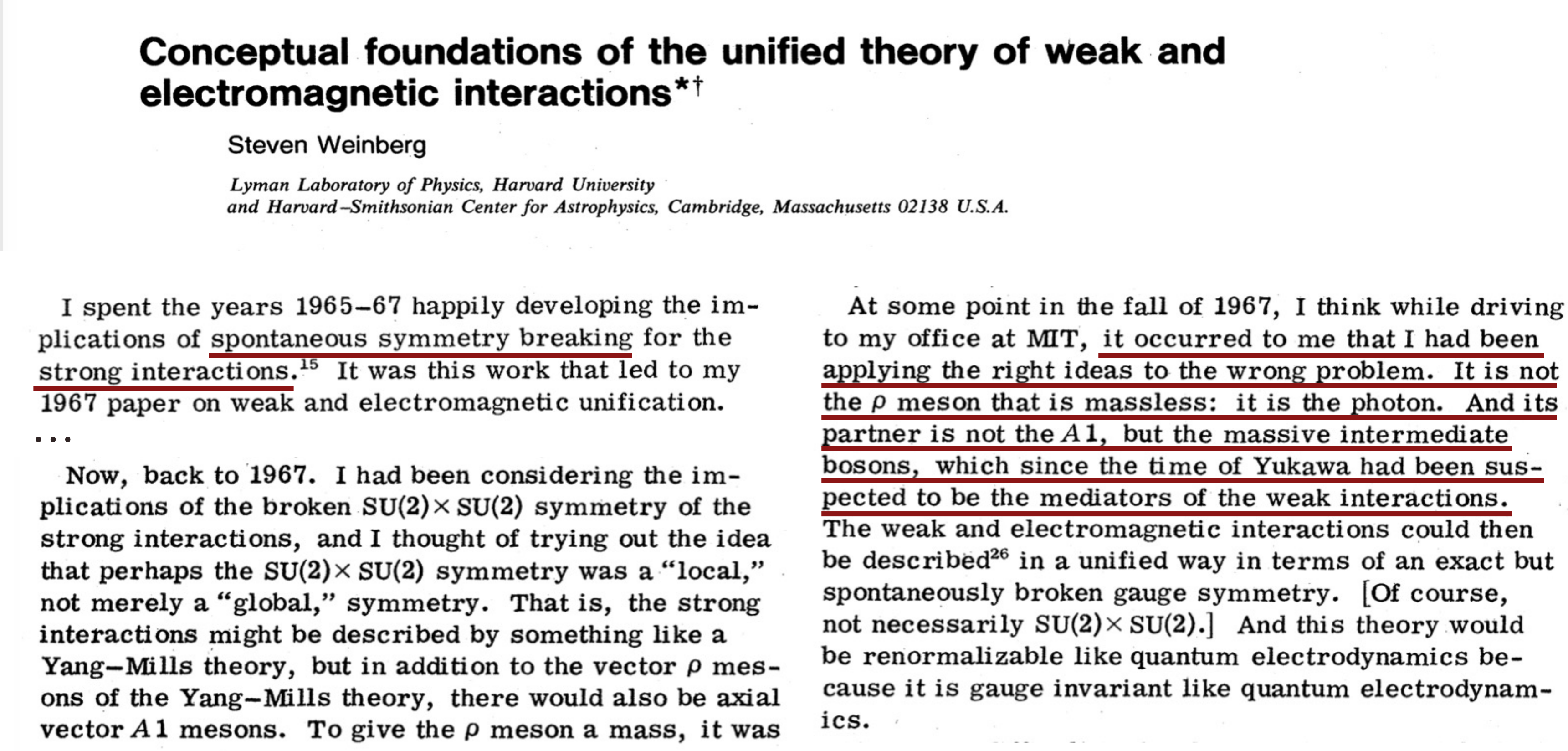


er than $\frac{3}{2}$. Of course our model has too many arbitrary features for these predictions to be taken very seriously, but it is worth keeping



Is this model renormalizable? We usually

Weinberg Nobel Lecture (1980)



Conceptual foundations of the unified theory of weak and electromagnetic interactions*†

Steven Weinberg

Lyman Laboratory of Physics, Harvard University
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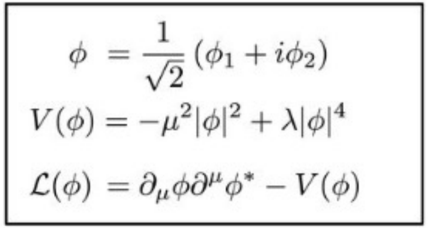
I spent the years 1965–67 happily developing the implications of spontaneous symmetry breaking for the strong interactions.[15] It was this work that led to my 1967 paper on weak and electromagnetic unification.

. . .

Now, back to 1967. I had been considering the implications of the broken SU(2)× SU(2) symmetry of the strong interactions, and I thought of trying out the idea that perhaps the SU(2)× SU(2) symmetry was a "local," not merely a "global," symmetry. That is, the strong interactions might be described by something like a Yang–Mills theory, but in addition to the vector ρ mesons of the Yang–Mills theory, there would also be axial vector $A1$ mesons. To give the ρ meson a mass, it was

At some point in the fall of 1967, I think while driving to my office at MIT, it occurred to me that I had been applying the right ideas to the wrong problem. It is not the ρ meson that is massless: it is the photon. And its partner is not the $A1$, but the massive intermediate bosons, which since the time of Yukawa had been suspected to be the mediators of the weak interactions. The weak and electromagnetic interactions could then be described[26] in a unified way in terms of an exact but spontaneously broken gauge symmetry. [Of course, not necessarily SU(2)× SU(2).] And this theory would be renormalizable like quantum electrodynamics because it is gauge invariant like quantum electrodynamics.

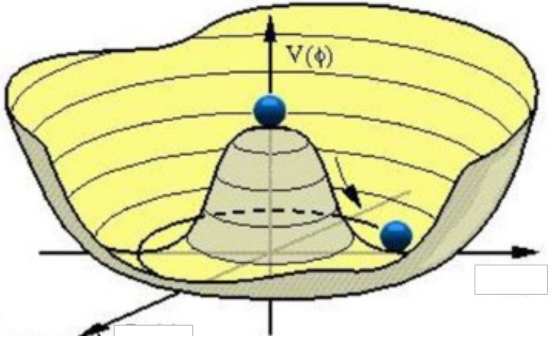
Formulation of Standard Model



$$\phi = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2)$$

$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

$$\mathcal{L}(\phi) = \partial_\mu\phi\partial^\mu\phi^* - V(\phi)$$



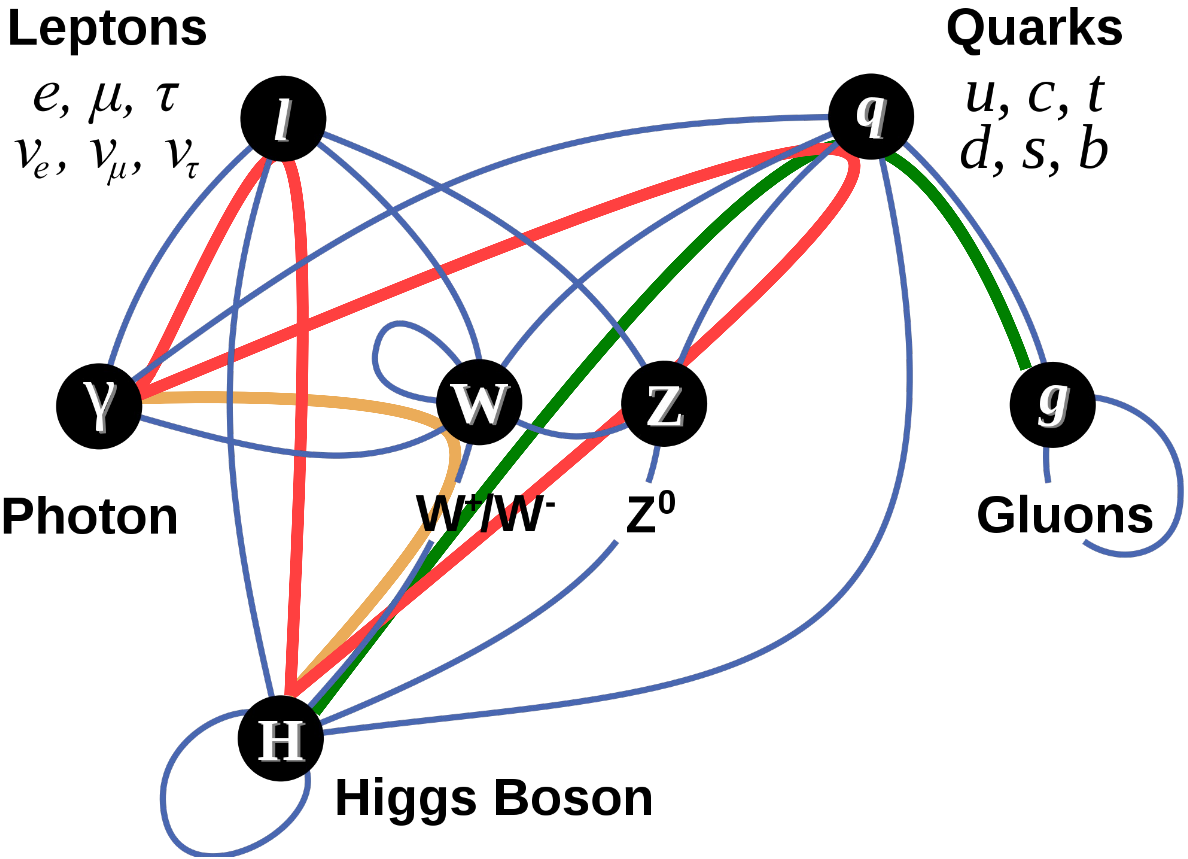
SM (Weinberg, 1967)

- Takes exactly the Glashow model
- Adds the concept of SSB and Higgs mechanism
- Estimation of W and Z masses
- Suggests ways to verify the existence of neutral currents

☐ Led to 48 years of experiments and to the construction of 9 accelerators:

- ISR, PETRA, SppS, TRISTAN, Tevatron, LEP, SLC, HERA, LHC, …

Standard Model Interactions



Following Years: Success!

1970

- ❑ Glashow, Iliopoulos and Maiani
    - Proposal of charm quark (GIM mechanism)

1971

- ❑ 't Hooft:
    - Proof of renormalizability of Yang-Mills theory with SSB invariance

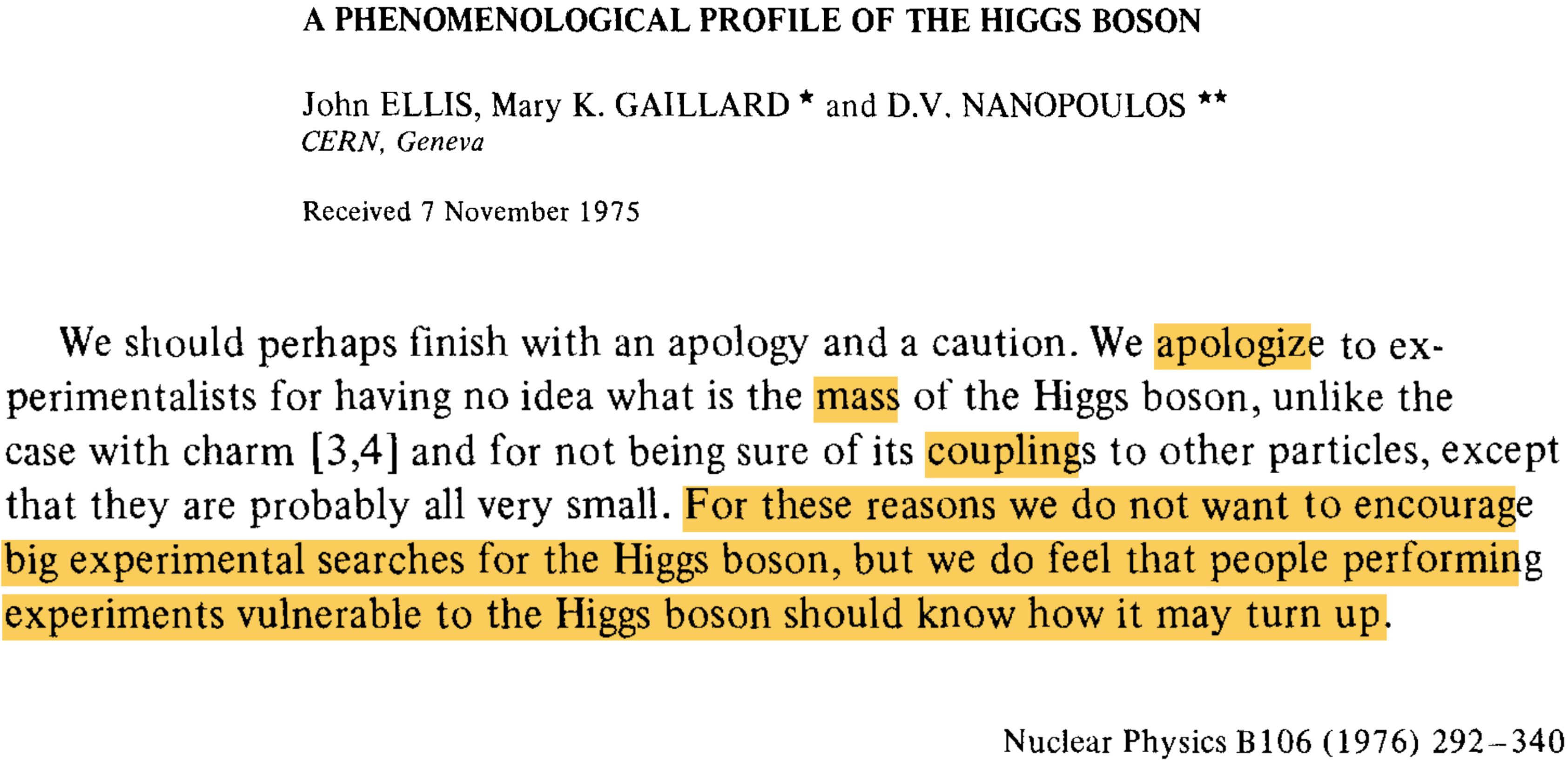
1973—1974

- ❑ Hasert et al. (CERN)
    - Experimental indication of the existence of weak neutral currents.
- ❑ Benvenuti et al. (Fermilab):
    - Confirmation of the existence of weak neutral currents

1983

- ❑ Arnison et al. (UA1 Collab.) and Banner et al. (UA2 Collab.):
    - Discovery of W and Z produced on-shell in proton-antiproton collisions

The Search for the Higgs Starts



A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Nuclear Physics B106 (1976) 292–340

Reproduces the low energy phenomenology.
The amplitudes respect unitarity bounds.
GIM mechanism requires family structure.
CP violation described by the CKM matrix.

Predicts weak interaction via neutral current.

Predicts the mass of the vector bosons (W and Z).

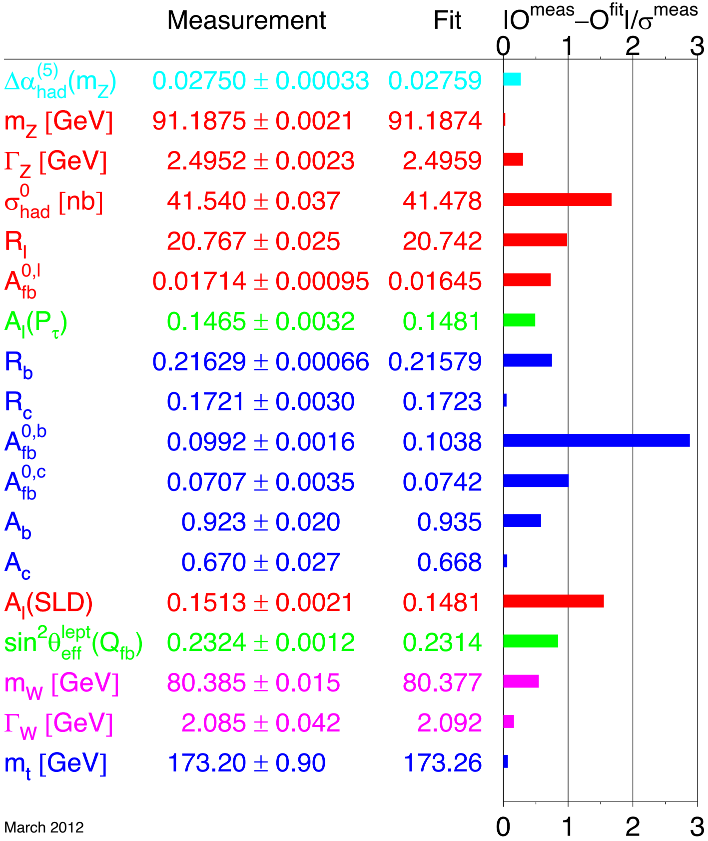
Predicts the existence of at least one Higgs boson.

Existence of W and Z were confirmed.
The existence of three families was established.
CP violation found also in the third generation.
Just the Higgs boson was missing!

With the simplest scenarios for New Physics being ruled out,
and plenty of models on the market,
none of which is compelling,
the status of theory is best summarized as
CONFUSION
Physics is again experimental science.

V. Rubakov
Alushta 2012

The Era LEP: A Decade of Precision Tests



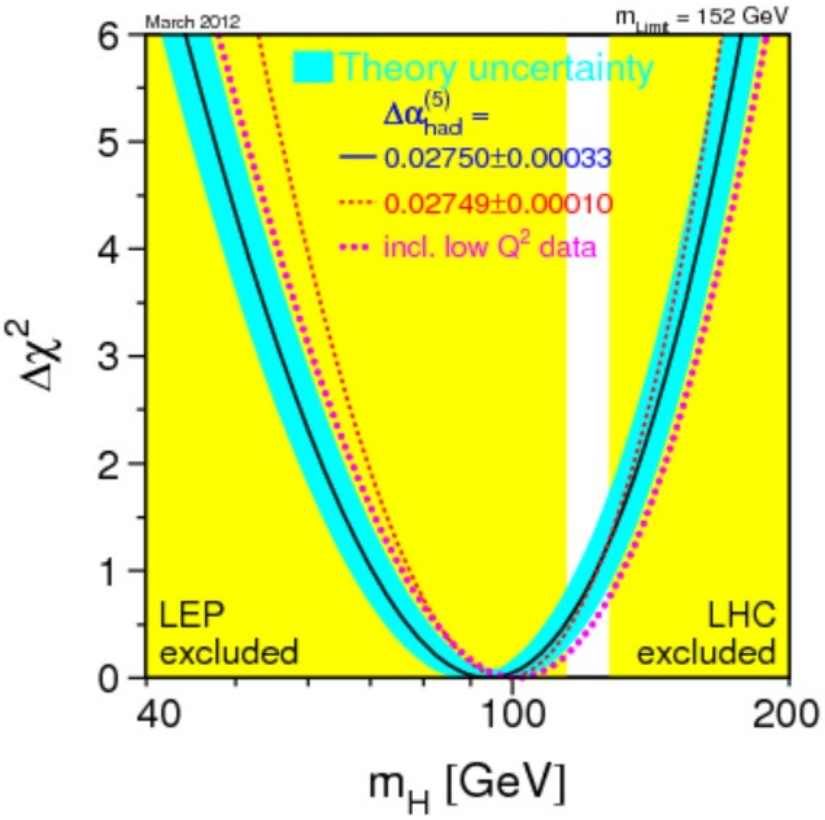
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26

March 2012

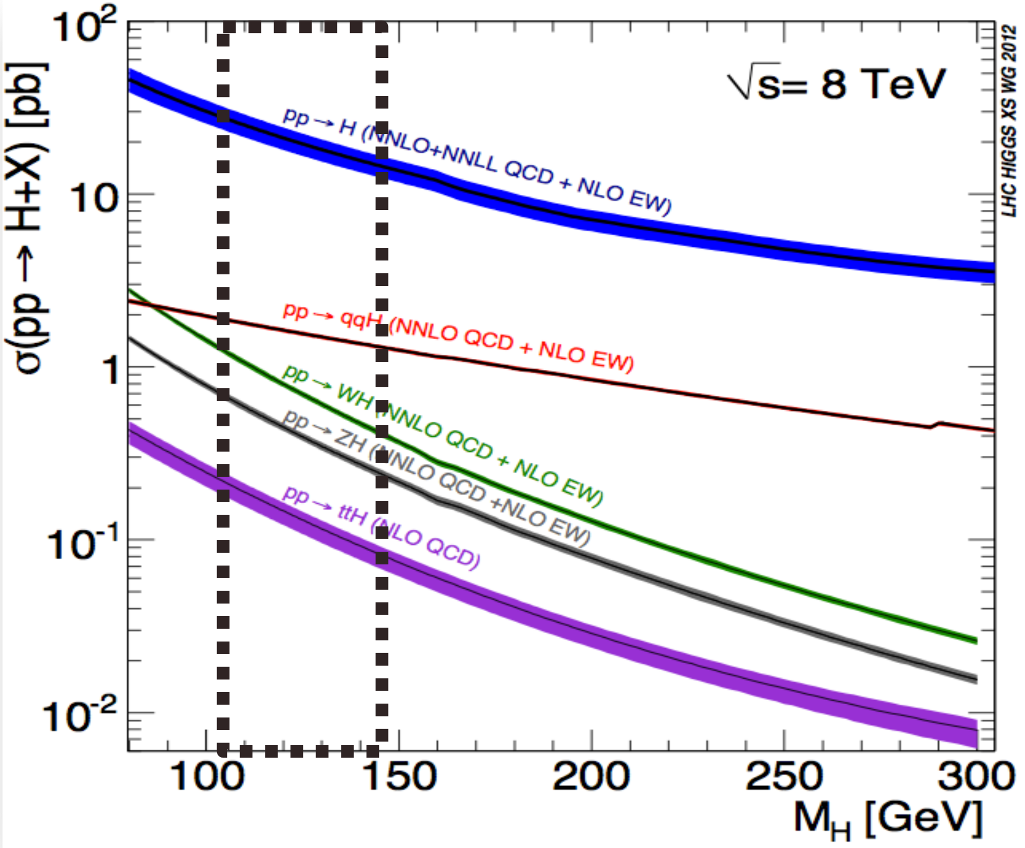
Higgs Expectations on March 2012

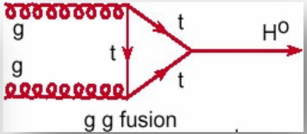
The LEP Electroweak WG

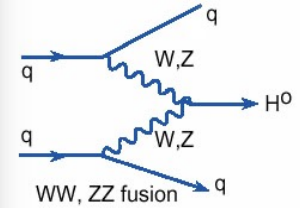
- ❑ Data from LEP, SLD, CDF, and D0, as a function of the M_H
- ❑ LEP-2 direct search limit 114 GeV
- ❑ LHC exclude 127 — 600 GeV
- ❑ Best value at 1 sigma (68% CL)
  - 94 + 29 – 24 GeV
  - = 70 — 123 GeV

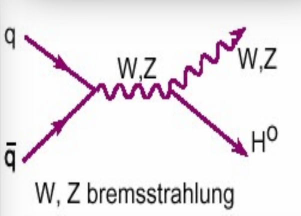


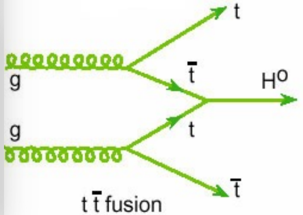
LHC Higgs Boson Production Mechanisms





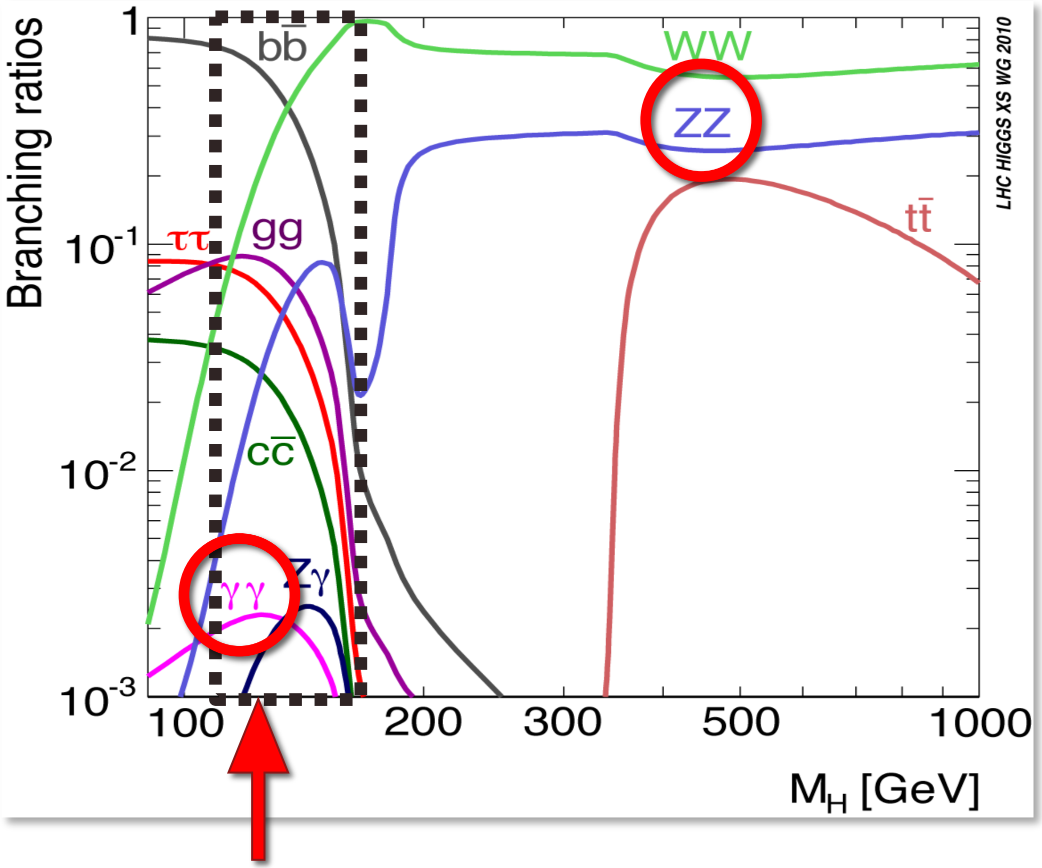




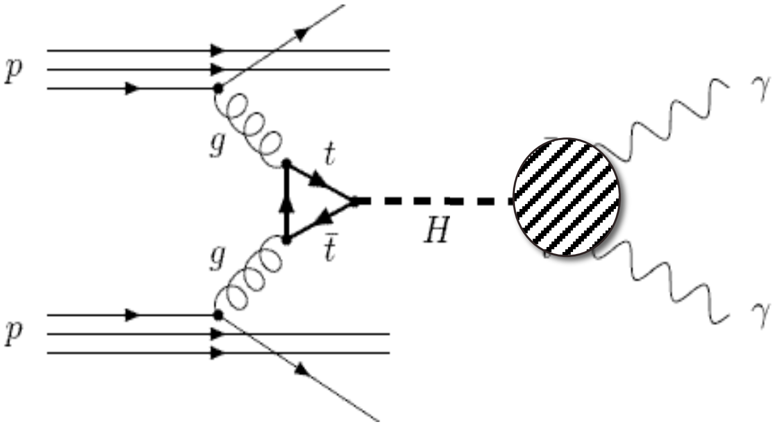


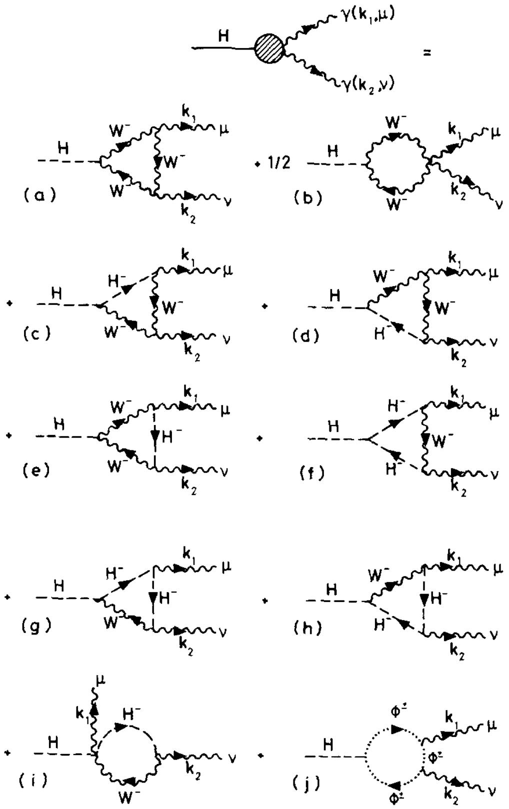
Higgs Boson Decay Channels

- 5 Channels
  - WW
  - ZZ
  - bb
  - ττ
  - ϒϒ
- Good mass resolution
  - ZZ → 4l
  - ϒϒ

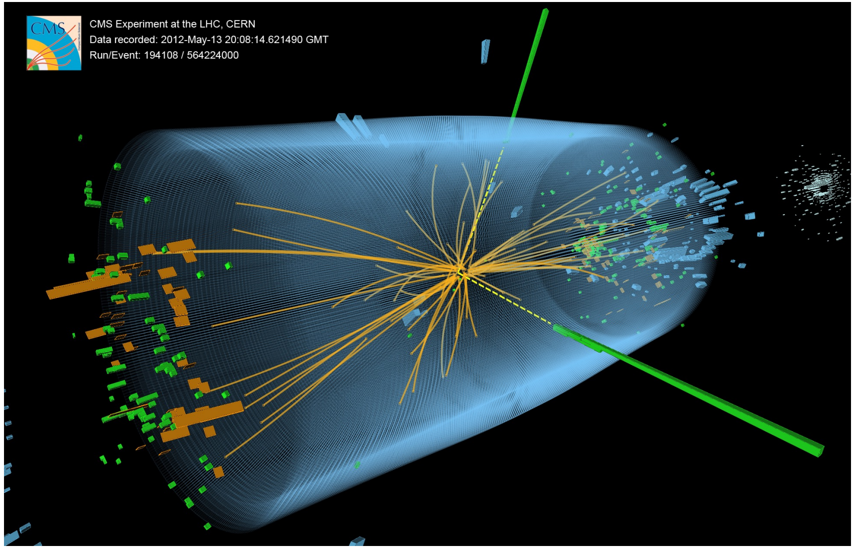


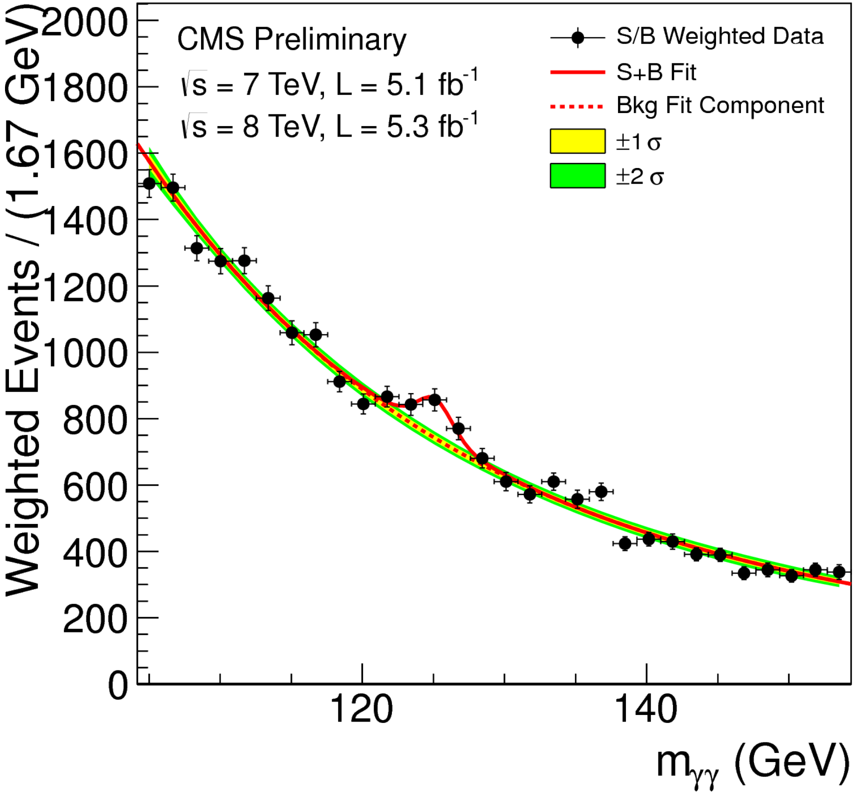
$pp \rightarrow gg \rightarrow H \rightarrow \gamma\gamma$



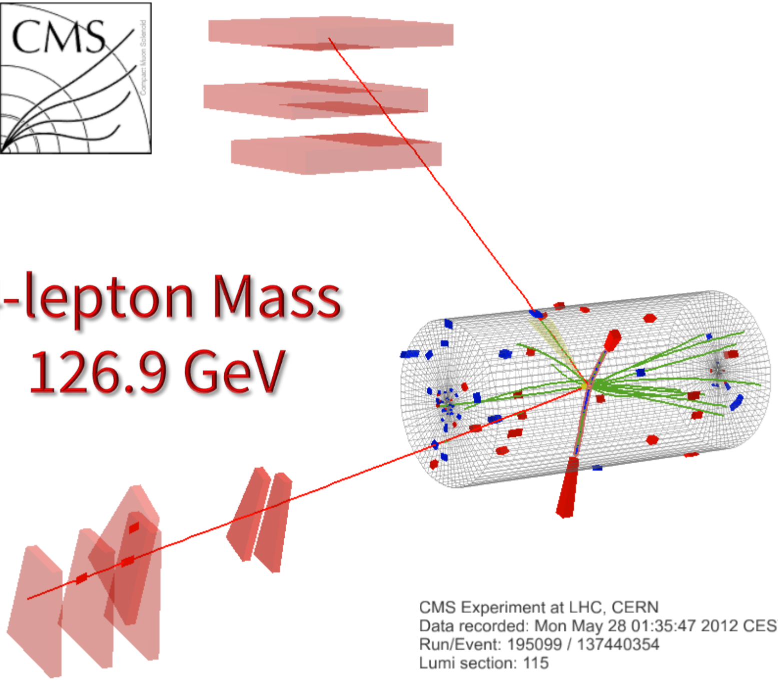


H → γγ Candidate



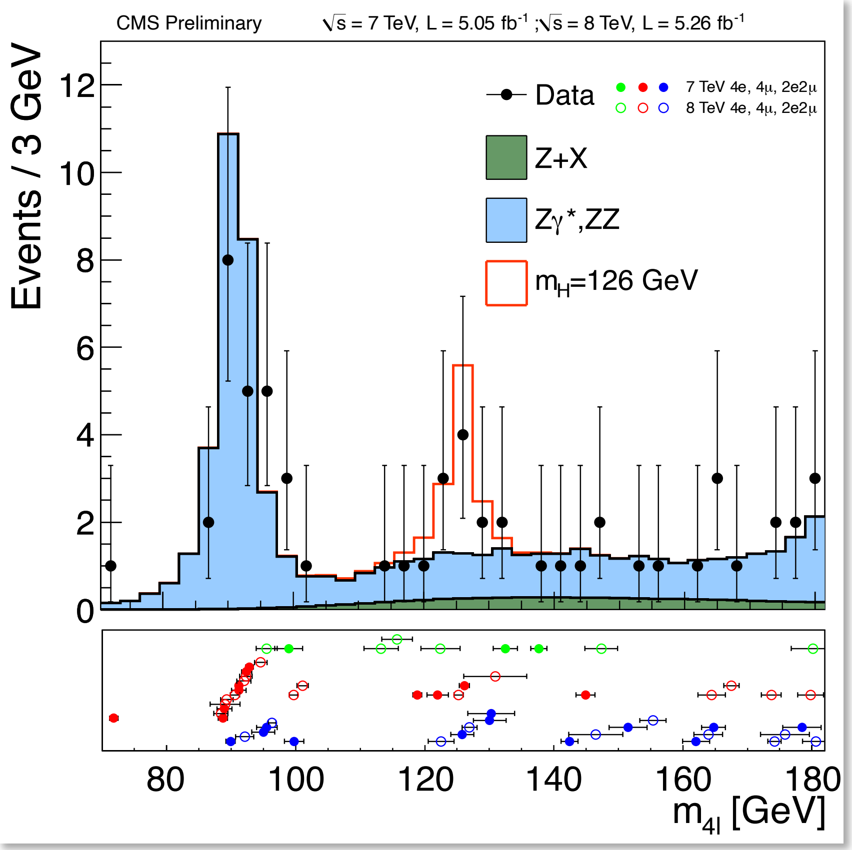


$H \to ZZ^* \to 4\ell$

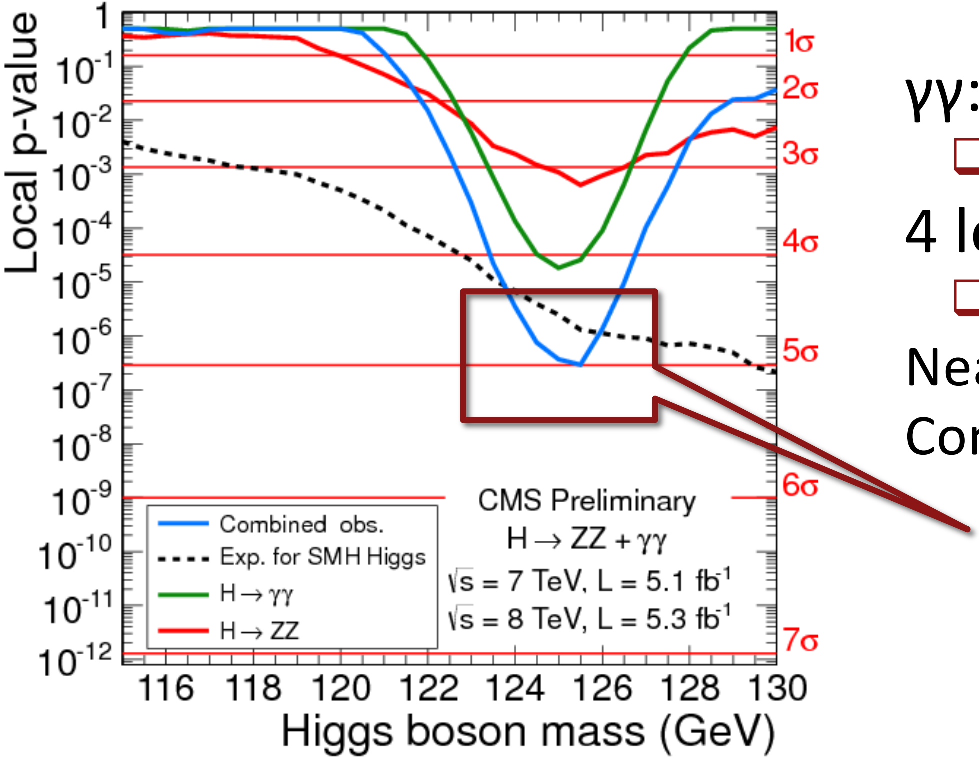


4-lepton Mass
126.9 GeV

CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:35:47 2012 CEST
Run/Event: 195099 / 137440354
Lumi section: 115



High-Mass Resolution Channels: γγ + 4l



4th July 2012

γγ:

- ☐ 4.1 σ excess

4 leptons:

- ☐ 3.2 σ excess

Near the same mass 125 GeV

Combined Significance:

5.0 σ

CMS Conclusion

A new boson was observed

with a mass of

$125.3 \pm 0.4\ (\text{stat}) \pm 0.5\ (\text{syst})\ \text{GeV}$

at significance level of

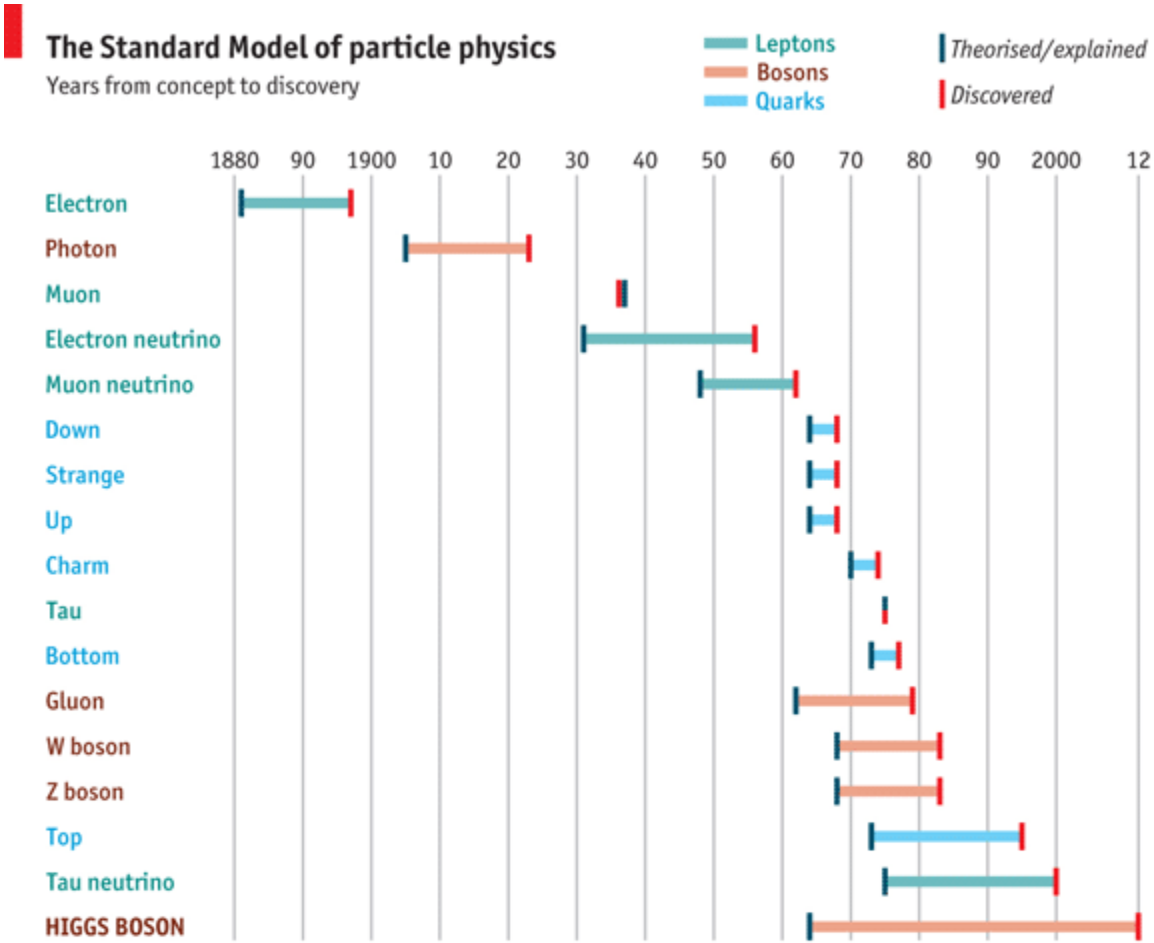
$5\ \sigma$

ICHEP — Melbourne

CERN — Geneva

4/July/2012

SPRACE — São Paulo



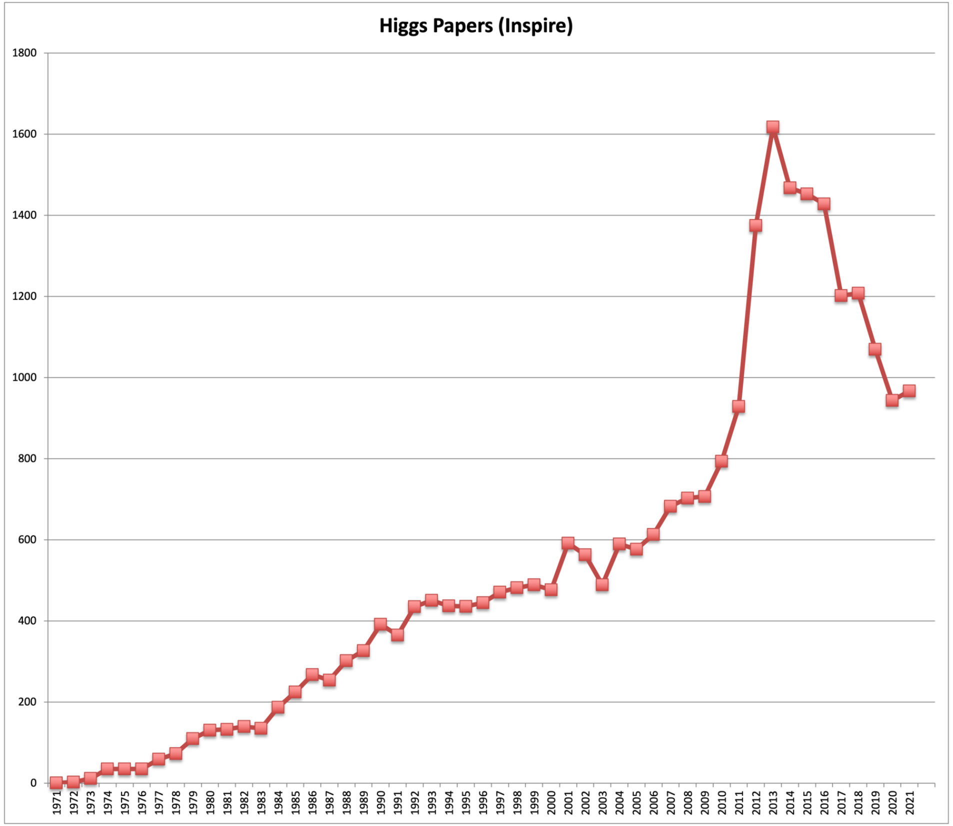
The Standard Model of particle physics

Years from concept to discovery

Source: *The Economist*

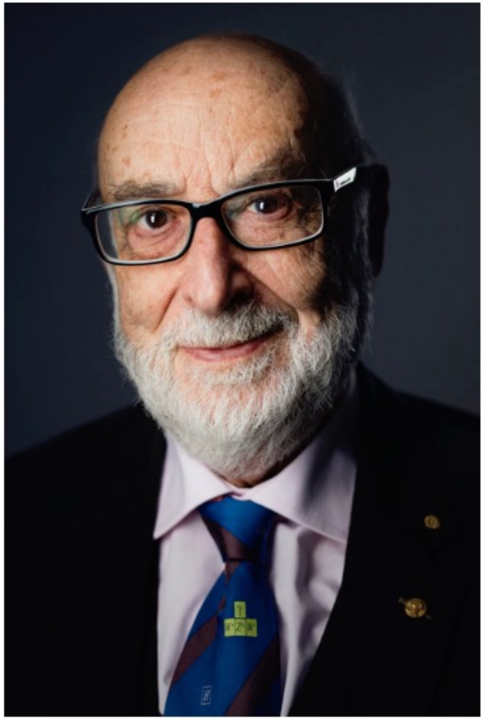
1964 — 2012 = 48 years

A Long Journey



The Nobel Prize in Physics 2013

8/October/2013



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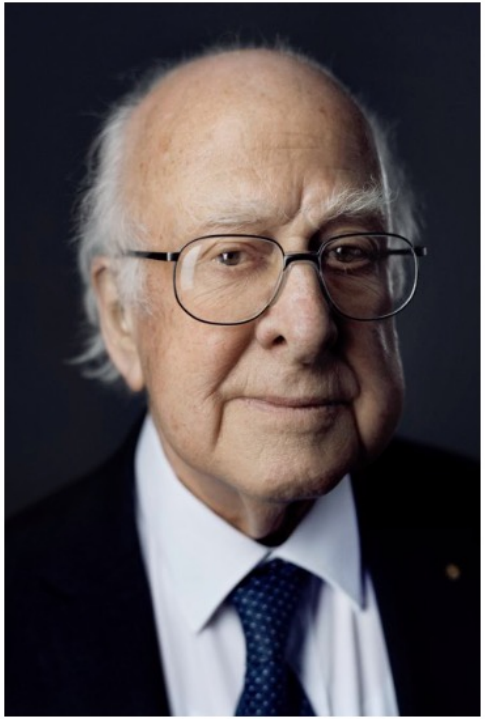
François Englert

Prize share: 1/2



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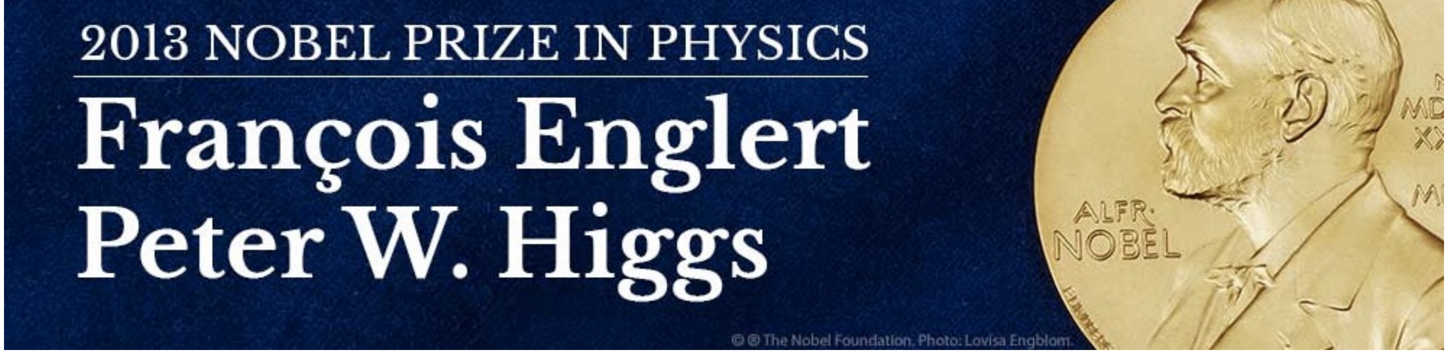
Peter W. Higgs

Prize share: 1/2



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The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

The minimal SM Higgs:
what was considered just as a toy model,
a temporary addendum to the gauge part of the SM,
is now promoted to the real thing.

Guido Altarelli

Nobel Symposium on LHC results
May 2013

Now this is not the end.
It is not even the beginning of the end.
But it is, perhaps,
the end of the beginning.

Winston Churchill

London, 9 November 1942.
Just after the 2nd Battle of El Alamein (Egypt)