The Brout-Englert-Higgs Theory of Electroweak Symmetry Breaking

James Wells
University of Michigan, Ann Arbor

Lecture 1, CERN, May 26, 2015

The BEH solution: Masses for All Particles

Standard Model solution: Break the gauge symmetries
By a single doublet charged under SU(2) and hypercharge:
The Higgs Boson.

Propagating Higgs particle

order parameter (vacuum expectation value

$$H = \begin{pmatrix} \frac{1}{\sqrt{2}}(h + v) + i\phi_1 \\ \phi_2 + i\phi_3 \end{pmatrix} \quad \text{where } v = 246\,\text{GeV}$$

Fluctuation of order parameter

Note: $\{W_T^\pm, Z_T^0\} + \{\phi_1, \phi_2, \phi_3\} \Rightarrow \{W_T^\pm, W_L^\pm, Z_T^0, Z_L^0\}$

HISTORICAL SLIDE – 3 YEARS OLD

Should we believe in the Higgs boson?

The Higgs boson is a speculative particle explanation for elementary particle masses.

Cons:

1. One particle carries all burdens of mass generation?
2. Fundamental scalar not known in nature.
3. Hasn't been found yet.
4. Too simplistic -- dynamics for vev not built in.
5. Idea not stable to quantum corrections.

Pros: Still consistent with experimental facts!

Physicists Find Elusive Particle Seen as Key to Universe

Pool photo by Denis Balibouse

Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson.

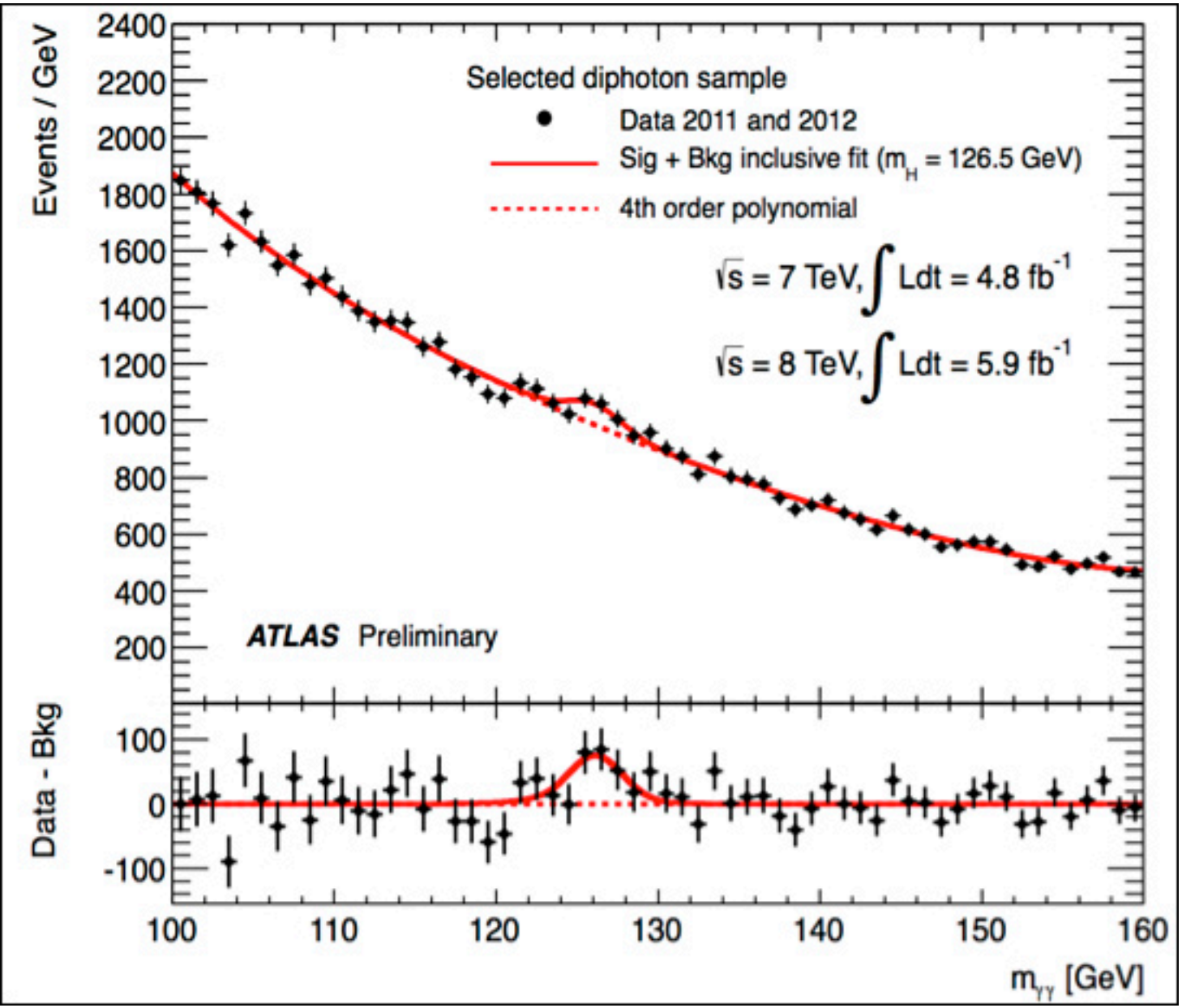
By DENNIS OVERBYE

Published: July 4, 2012 | 122 Comments

$$\text{mass} = 134 \times M_{\text{Hydrogen}} = M_{\text{Cesium}}$$

New York Times

For example:



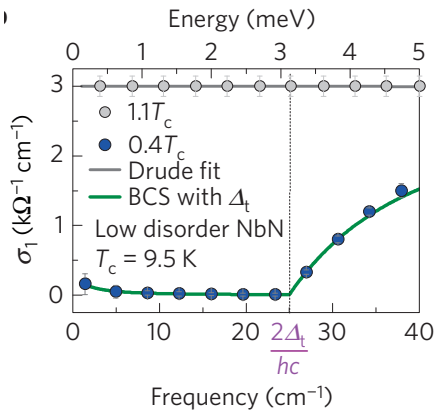
Tiny bump was seen at 126 GeV

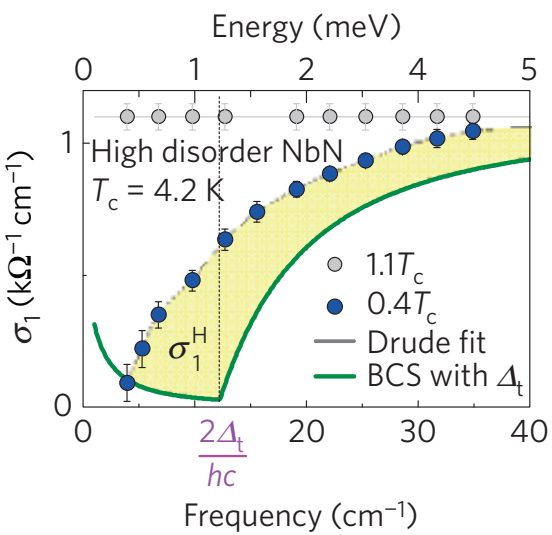
Meanwhile, recently, our condensed matter friends claim to have seen the Higgs boson too!

January 26, 2015 Nature

The Higgs mode in disordered superconductors close to a quantum phase transition

Daniel Sherman[1,2†], Uwe S. Pracht[2], Boris Gorshunov[2,3,4], Shachaf Poran[1], John Jesudasan[5], Madhavi Chand[5], Pratap Raychaudhuri[5], Mason Swanson[6], Nandini Trivedi[6], Assa Auerbach[7], Marc Scheffler[2], Aviad Frydman[1*] and Martin Dressel[2]





BCS theory → $m_H \sim 2\Delta$ and very short lived and hidden

Highly disordered SC (HDSC):
- high resistivity in normal state
- Elastic scattering length reduces ~ λ_F
- e's localize, cooper pairs not made of "free electrons"
- Localization leads to insulator – cooper pairs in insulators
- T_c can reduce near zero, Quantum Critical Point (QCP)

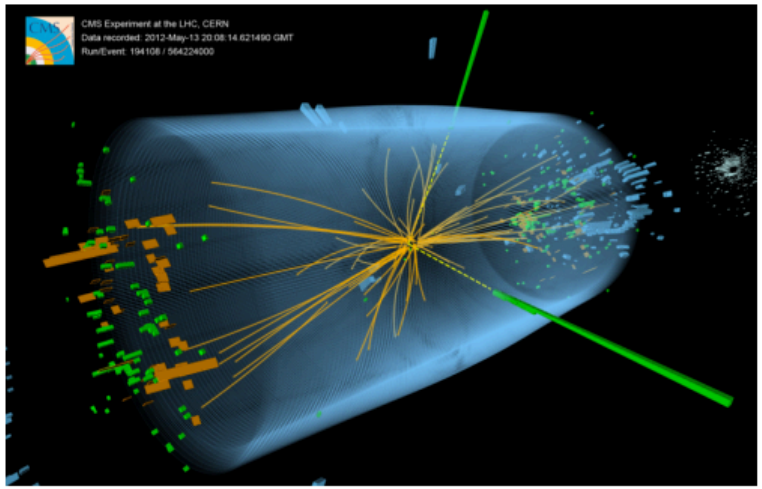
Higgs signal:
- Higgs boson softens below 2Δ in HDSC (Podolsky et al. 2011)
- Excess conductivity in sub-gap region
- Tunneling and THz spectroscopy probes of HDSC
- Thin films (2d) of NbN and InO near criticality (insulator-SC transition)

$$\hat{\sigma}(\omega) = \sigma_1(\omega) + i\sigma_2(\omega) = \underbrace{A\rho_s\delta(\omega) + \hat{\sigma}^{qp}(\omega)}_{\hat{\sigma}^{BCS}(\omega)} + \hat{\sigma}^{H}(\omega)$$

$$\sigma_1^{H}(\omega) = \sigma_1^{exp}(\omega) - \sigma_1^{BCS}(\omega)$$

Researchers first to observe Higgs boson analogue in superconductors

Feb 19, 2015



phys.org

A graphic shows particle traces extending from a proton-proton collision at the Large Hadron Collider in 2012. The event shows characteristics expected from the decay of the Standard Model Higgs boson to a pair of photons. Further analysis of … more

The Nobel Prize-winning discovery of the Higgs boson - the "God particle" believed responsible for all the mass in the universe - took place in 2012 at CERN's Large Hadron Collider, an underground facility where accelerated sub-atomic particles zip around the circumference of a 27-kilometer (16.9-mile) ring-shaped tunnel. But what goes around comes around: more than 50 years ago, the first hint of Higgs was inspired by the study of superconductors - a special class of metals that, when cooled to very low temperatures, allow electrons to move without resistance.

Feat

Once-da
patients
2015

NASH a
of death

Moreover, the robust nature of the newly-observed Higgs mode in superconductors could make it easier for scientists to study the still-controversial "God particle" - the elusive "missing link" in the Standard Theory of particle physics believed responsible for imparting mass to all the matter in the universe. Thanks to this new approach, it may soon be possible to solve long-standing mysteries of fundamental physics, through experiments conducted - not in a multi-billion dollar accelerator complex - but on a laboratory tabletop.

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'God Particle' analogue spotted outside a supercollider: Scientists find Higgs mode in a superconductor

- God Particle is believed to be responsible for all the mass in the universe
- Particle was discovered in 2012 using a Cern's supercollider in Geneva
- Superconductor experiment suggests the particle could be detected without the huge amounts of energy used at by the Large Hadron Collider

Misconceptions among non-experts can be humorous

However, disconnect remains with our condensed matter friend…

They think we are naïve!

Nature, published 26 January 2015

news & views

SUPERCONDUCTIVITY

Higgs, Anderson and all that

The Higgs mechanism is normally associated with high energy physics, but its roots lie in superconductivity. And now there is evidence for a Higgs mode in disordered superconductors near the superconductor–insulator transition.

Philip W. Anderson

There is one further question. If superconductivity does not require an explicit Higgs in the Hamiltonian to observe a Higgs mode, might the same be true for the 126 GeV mode? As far as I can interpret what is being said about the numbers, I think that is entirely plausible. Maybe the Higgs boson is fictitious!

Deep connection between superconductivity and the theory of electroweak interactions.

Pre-history

1896: Radiation discovered Becquerel

1911 Onnes discovered superconductivity -- Hg with $T_c = 4.2$ K

1914: (A,Z) → (A,Z+1) + β^- with β particles understood to be electrons well understood

1930: Pauli introduces neutrino (A,Z) → (A,Z+1) + β^- + ν to retain energy conservation

1932: Chadwick discovers neutron.

1933 Meissner effect -- Superconductors expel magnetic fields (perfect diamagnet)

1934 Londons theory (J ~ A) -- explained Meissner effect, derived penetration depth

1933: Heisenberg, Majorana, Ivanenko posited nuclei are bound states of protons and neutrons.

1934: Fermi's theory of β decay : "effective theory" of the electroweak interactions

Superconductivity :: 1950 - 1957

Development of Ginzburg-Landau Theory

Landau theory of Phase Transitions applied to Superconductivity

Londons' theory success (explained Meissner) but had problems, including surface interface energy, not allowing destruction of SC state by a current, etc.

When you have a hammer (Landau theory of P.T. 1937) everything looks like a nail (superconductivity).

Superconductivity is a P.T. with order parameter n_s (Ginzburg-Landau 1950).

Superconducting state is macroscopic QM wavefunction $\psi(r)$ with $n_s \sim |\psi|^2$.

Candidate for application of Landau's general mean-field theory of phase transitions

1) Identify ψ as order parameter where $\psi=0$ for $T > T_c$ and ψ nonzero with $T < T_c$.

2) Expand free energy difference between SC state and normal state and minimize.

$$F_{SC} - F_N = \alpha|\psi|^2 + \frac{\beta}{2}|\psi|^4 + \cdots + \frac{(-i\hbar\nabla - qA)^2}{2m} - \int_0^B \vec{M} \cdot d\vec{B}$$

Ginzburg-Landau Theory (cont.)

Let B=0 and ignore spatial variations at the moment. Order parameter is density of superconducting carriers $|\psi|^2 \sim n_s$

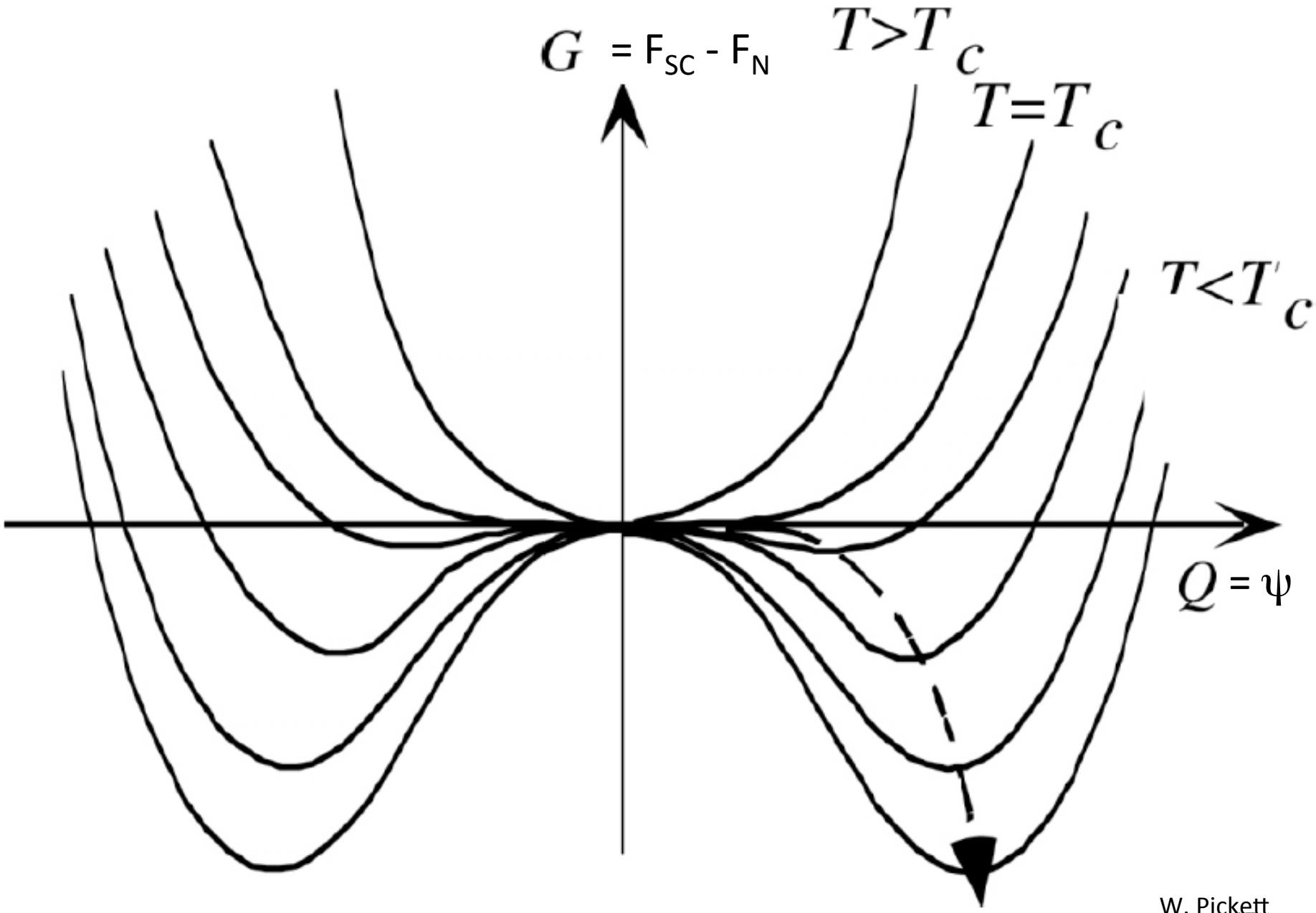
$$F_{SC} - F_N = \alpha|\psi|^2 + \frac{\beta}{2}|\psi|^4$$

Minimize the free-energy:

$$|\psi|^2 = -\frac{\alpha}{\beta} > 0 \quad (\text{if } \alpha < 0,\ \beta > 0)$$

$$F_{SC} - F_N = -\frac{\alpha^2}{2\beta} < 0 \quad (F_{SC} \text{ is lower energy state})$$

With finite temperature $\alpha \rightarrow \alpha\,(1\text{-}T/T_c)$ :: $T > T_c$ changes α sign

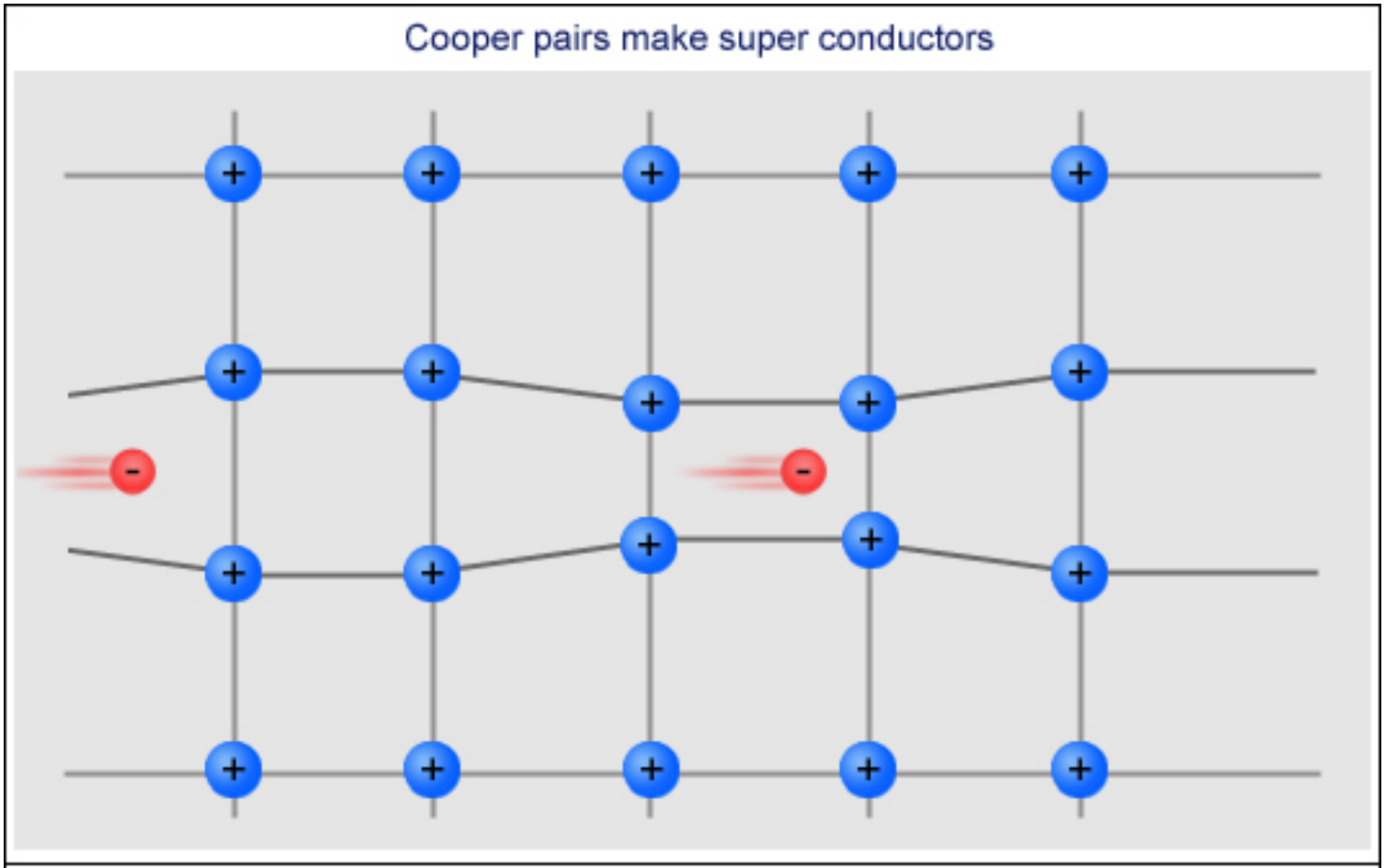


W. Pickett

Superconductivity :: 1957

BCS Theory

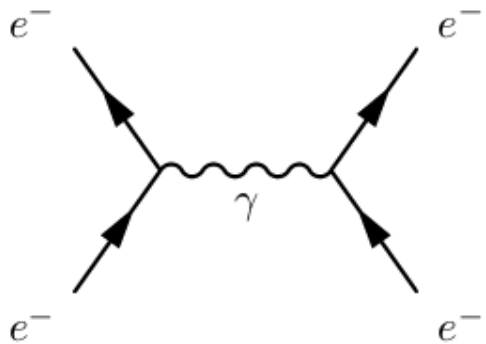
Brief BCS theory redux (1957)



At extremely low temperatures, an electron can draw the positive ions in a superconducting material towards it. This movement of the ions creates a more positive region that attracts another electron to the area.

abc.net.au

Repulsive photon-mediated interactions dominate at short distances, but **attractive** phonon-mediated interactions dominate at larger distances.



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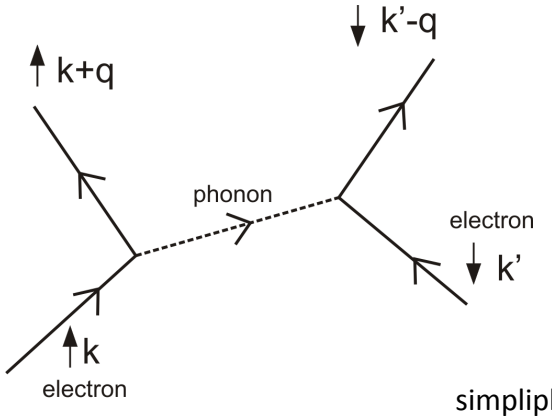

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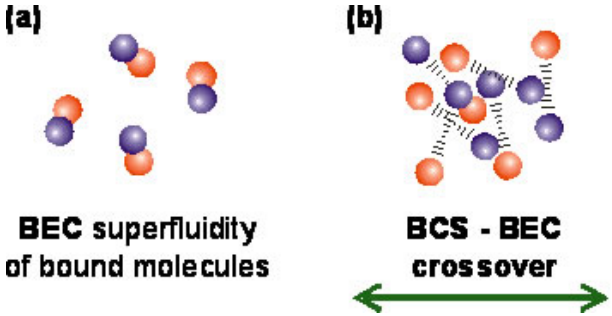
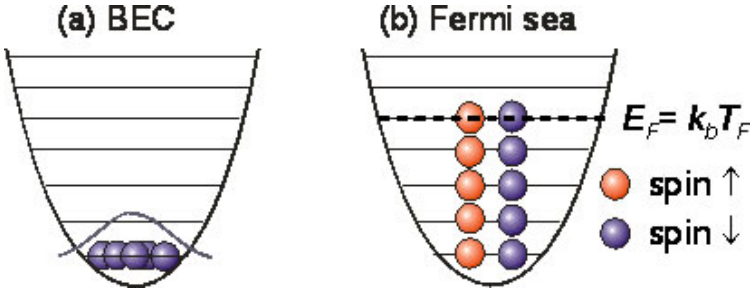




greiner.harvard.edu

Particle Physics :: early mid 1960s

Nambu, then Glashow-Weinberg-Salam

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
(Received July 23, 1959)

Ideas and techniques known in quantum electrodynamics have been applied to the Bardeen-Cooper-Schrieffer theory of superconductivity. In an approximation which corresponds to a generalization of the Hartree-Fock fields, one can write down an integral equation defining the self-energy of an electron in an electron gas with phonon and Coulomb interaction. The form of the equation implies the existence of a particular solution which does not follow from perturbation theory, and which leads to the energy gap equation and the quasi-particle picture analogous to Bogoliubov's.

The gauge invariance, to the first order in the external electromagnetic field, can be maintained in the quasi-particle picture by taking into account a certain class of corrections to the charge-current operator due to the phonon and Coulomb interaction. In fact, generalized forms of the Ward identity are obtained between certain vertex parts and the self-energy. The Meissner effect calculation is thus rendered strictly gauge invariant, but essentially keeping the BCS result unaltered for transverse fields.

It is shown also that the integral equation for vertex parts allows homogeneous solutions which describe collective excitations of quasi-particle pairs, and the nature and effects of such collective states are discussed.

- First to understand strict gauge invariance despite Meissner effect

PHYSICAL REVIEW VOLUME 122, NUMBER 1 APRIL 1, 1961

Dynamical Model of Elementary Particles Based on an Analogy with Superconductivity. I*

Y. NAMBU AND G. JONA-LASINIO†
The Enrico Fermi Institute for Nuclear Studies and the Department of Physics, The University of Chicago, Chicago, Illinois
(Received October 27, 1960)

It is suggested that the nucleon mass arises largely as a self-energy of some primary fermion field through the same mechanism as the appearance of energy gap in the theory of superconductivity. The idea can be put into a mathematical formulation utilizing a generalized Hartree-Fock approximation which regards real nucleons as quasi-particle excitations. We consider a simplified model of nonlinear four-fermion interaction which allows a γ_5-gauge group. An interesting consequence of the symmetry is that there arise automatically pseudoscalar zero-mass bound states of nucleon-antinucleon pair which may be regarded as an idealized pion. In addition, massive bound states of nucleon number zero and two are predicted in a simple approximation.

The theory contains two parameters which can be explicitly related to observed nucleon mass and the pion-nucleon coupling constant. Some paradoxical aspects of the theory in connection with the γ_5 transformation are discussed in detail.

From the Nambu Jona-Lasinio 1961 paper (p. 346):

Once we make this analogy, we immediately notice further consequences of special interest. It has been pointed out by several people[3,5–8] that in a refined theory of superconductivity there emerge, in addition to the individual quasi-particle excitations, collective excitations of quasi-particle pairs. (These can alternatively be interpreted as moving states of bare electron pairs which are originally precipitated into the ground state of the system.) In the absence of Coulomb interaction, these excitations are phonon-like, filling the gap of the quasi-particle spectrum.

- Arguably first place to hint/reveal the "Higgs mechanism" (F. Close, Infinity Puzzle)

Nambu was motivated mostly by understanding bound states of the strong interaction – mass provided by gap.

His ideas laid the foundation for particle physicists' understanding of spontaneous symmetry breaking, mass generation and gauge invariance.

Nobel Prize 2008 – "*for the discovery of the mechanism of spontaneous symmetry breaking in subatomic physics.*"

Application of his ideas to the weak interaction were to come much later in chiral symmetry breaking (early 1960s), Higgs theory (1964), technicolor theory (1979), and top condensate theories (mid 1990s and beyond).

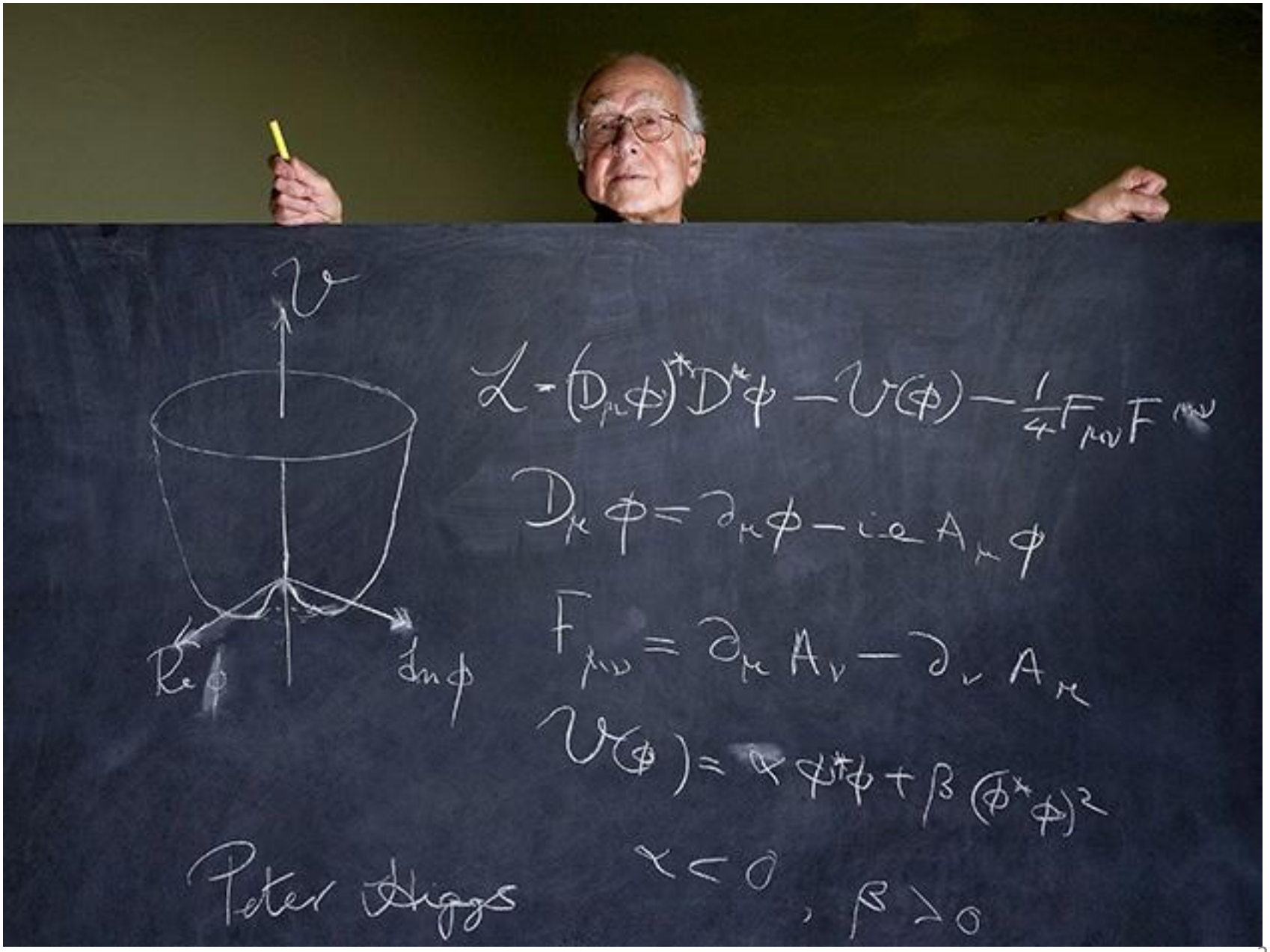
CM Physics: Simple MFT place-holder theory (GL theory) – this was obviously not the fundamental theory.

That was 1950's physics!

Sophisticated dynamical theory (BCS) – the "true theory"

However,
Our CM friends open up newspapers and magazines today and they see pictures like this (next page):

Here's the theory! Higgs, Brout, Englert as well as Guralnik, Hagen, Kibble.



Just what did Peter Higgs (and others – Brout and Englert in particular) do?

1. Understood spontaneous symmetry breaking in *relativistic* QFT setting (there was confusion before).

2. Showed how gauge fields (abelian and non-abelian) eat massless goldstone modes.

3. First (Higgs) to explicitly say there should be a propagating massive scalar particle ("incomplete multiplets" propagating)

This was of course important, ground-breaking work

‘t Hooft. “The Evolution of QFT”. *Proc. of the Standard Theory up to the Higgs discovery*. 17 March 2015 (1503.05007)

An other obscure corner was investigated by Peter Higgs [22], Robert Brout and François Englert [23]. They enjoyed little attention when they argued that the symmetry employed by Yang and Mills had to be spontaneously broken. The reason for that was that this alley had also been closed by the “experts”. There was the famous ‘Goldstone Theorem’ [24]: *Whenever a symmetry is spontaneously broken, at least one particle must become massless.* Indeed, in the Gell-Mann Lévy Model, the pion behaves as a massless particle. The weak interaction, however, did not seem to involve massless objects. Higgs, Brout and Englert saw no massless particles in their models either, but a major fraction of the community did not believe them. So they were mainly being ignored. Veltman paid no attention at all to formal mathematics, so he believed neither Higgs, Brout and Englert, nor Jeffrey Goldstone. He only believed the experiments, and his computer.

Subsequently gives credit to Weinberg to piecing together particles + Higgs in Standard Model. No mention anywhere of Anderson.

Anderson, Nature January 2015

supplied. Another roadblock was the apparent necessity of allowing a number of Goldstone bosons into the theory, which would mean that the theory would be full of massless bosons — which didn't exist! When I heard in 1962 that people considered this a real obstacle, I sent off a short paper[8] saying "forget it — the gap is empty in a real superconductor!". The gauge field — the photon in a superconductor — and the matter field, the Goldstone boson, combine and make massive vector bosons (plasmons for superconductors, W and Z bosons for particles).

What Anderson really said in 1962/63 :

From the Conclusions (Last paragraph in the paper):

Spin waves also are known to interact strongly with magnetostatic forces at very long wavelengths,[14] for rather more obscure and less satisfactory reasons. 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.

P.W. Anderson, "Plasmons, Gauge Invariance, and Mass," Phys Rev 130 (1963) 439.

Why did Anderson waffle?

Likely because confusion abounded about Goldstone's theorem (massless states on SSB) domain of applicability – relativistic vs non-relativistic theories in particular.

Debates and confusions percolated into the literature in early 1964 (Klein, Lee, Gilbert, etc.)

Brout, Englert, Higgs were first to nail it down.

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

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

Received 27 July 1964

Recently a number of people have discussed the Goldstone theorem [1,2]: that any solution of a Lorentz-invariant theory which violates an internal symmetry operation of that theory must contain a massless scalar particle. Klein and Lee [3] showed that this theorem does not necessarily apply in non-relativistic theories and implied that their considerations would apply equally well to Lorentz-invariant field theories. Gilbert [4], however, gave a proof that the failure of the Goldstone theorem in the nonrelativistic case is of a type which cannot exist when Lorentz invariance is imposed on a theory. The purpose of this note is to show that Gilbert's argument fails for an important class of field theories, that in which the conserved currents are coupled to gauge fields.

Following the procedure used by Gilbert [4], let us consider a theory of two hermitian scalar fields

Gilbert had "proved" that massless Goldstones were absolutely required in Lorentz invariant theories, whereas there were outs in non-relativistic theories (like superconductors, etc.).

Brout, Englert, Higgs first showed that "Gilbert's argument fails for … field theories … coupled to gauge fields" as Higgs says.

[Gilbert left physics and went on to win Nobel Prize in chemistry!]

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

In a recent note[1] it was shown that the Goldstone theorem,[2] that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if the conserved currents associated with the internal group are coupled to gauge fields. The purpose of the present note is to report that, as a consequence of this coupling, the spin-one quanta of some of the gauge fields acquire mass; the longitudinal degrees of freedom of these particles (which would be absent if their mass were zero) go over into the Goldstone bosons when the coupling tends to zero. This phenomenon is just the relativistic analog of the plasmon phenomenon to which Anderson[3] has drawn attention: that the scalar zero-mass excitations of a superconducting neutral Fermi gas become longitudinal plasmon modes of finite mass when the gas is charged.

By this paper it's all sorted. Relativistic gauge theories bypass Goldstone's theorem, vector bosons obtain mass (longitudinal modes), and later he first introduces what we now call the Higgs boson.

It has been a dream of many physicists that there are fancy dynamics that underlie the “simple” Brout-Englert-Higgs theory.

There are many ideas, but let us close with the most brief discussion of fermion condensate theories of EWSB.

Technicolor and/or Composite Higgs theories

Postulate to pursue: Electroweak symmetry breaking happens via a condensate of fermions.

It is fair to say that this approach was largely inspired by superconductivity, and has as its origin in Nambu's foray into the field in 1960 (but he started thinking in 1956) after learning about BCS theory (Bardeen, Cooper, Schrieffer 1957).

Our best shot at a BCS theory of particle physics ….

Around mid 90's it was becoming obvious m_{top} large (175 GeV). Opportunity!

Only viable idea with known particles was condensing $<t_L t_R>$.

Superconducting royalty emerged! (Familiar names of Bardeen, Nambu & descendants)

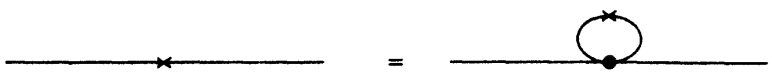
PHYSICAL REVIEW D VOLUME 41, NUMBER 5 1 MARCH 1990

Minimal dynamical symmetry breaking of the standard model

William A. Bardeen, Christopher T. Hill, and Manfred Lindner
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510
(Received 21 July 1989; revised manuscript received 2 November 1989)

We formulate the dynamical symmetry breaking of the standard model by a top-quark condensate in analogy with BCS theory. The low-energy effective Lagrangian is the usual standard model with supplemental relationships connecting masses of the top quark, W boson, and Higgs boson which now appears as a $\bar{t}\,t$ bound state. Precise predictions for m_t and m_H are obtained by abstracting the compositeness condition for the Higgs boson to boundary conditions on the renormalization-group equations for the full standard model at high energy.

$$L = L_{\text{kinetic}} + G(\bar{\Psi}^{ia}_{L} t_{Ra})(\bar{t}^{b}_{R} \Psi_{Lib})$$



Gap equation

$$m_t = -\tfrac{1}{2} G \langle \bar{t}t \rangle$$

$$= 2GN_c m_t \frac{i}{(2\pi)^4} \int d^4 l (l^2 - m_t^2)^{-1}$$

$$G^{-1} = \frac{N_c}{8\pi^2}[\Lambda^2 - m_t^2 \ln(\Lambda^2/m_t^2)] \,, \tag{2.3}$$

which has solutions for sufficiently strong coupling, $G \geq G_c = 8\pi^2/N_c\Lambda^2$ where G_c is the "critical" coupling constant.

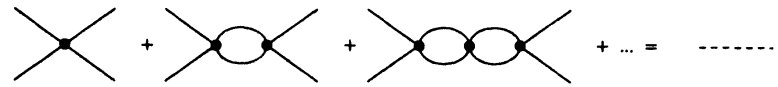


FIG. 2. Bubble sum generated by the four-fermion interaction.

$$\Gamma_s(p^2) = -\tfrac{1}{2}G - (\tfrac{1}{2}G)^2 i \int d^4x\, e^{ipx} \langle T\, \bar{t}t(0)\bar{t}t(x) \rangle_{\text{connected}} + \cdots \,. \tag{2.4}$$

A useful technical trick for evaluating this amplitude while simultaneously implementing the gap equation is given in Appendix A. The result is

$$\Gamma_s(p^2) = \frac{1}{2N_c} \Big[(p^2 - 4m_t^2)(4\pi)^{-2} \times \int_0^1 dx \ln\{\Lambda^2/[m_t^2 - x(1-x)p^2]\} \Big]^{-1} .$$

Higgs-like boundstate

$$\Gamma_p(p^2) = -\tfrac{1}{2}G - (\tfrac{1}{2}G)^2 i \times \int d^4x\, e^{ipx} \langle T\, \bar{t}\gamma_5 t(0)\bar{t}\gamma_5 t(x) \rangle_{\text{connected}} + \cdots \,. \tag{2.6}$$

By similar manipulations as in Eq. (2.5) and use of the gap equation we find

$$\Gamma_p(p^2) = \frac{1}{2N_c} \Big[(p^2)(4\pi)^{-2} \times \int_0^1 dx \ln\{\Lambda^2/[m_t^2 - x(1-x)p^2]\} \Big]^{-1}$$

Goldstone modes

W boson propagator and the vev f (gap).

$$\frac{1}{g_2^2} D^W_{\mu\nu}(p)^{-1} = \frac{1}{g_2^2}(p_\mu p_\nu - g_{\mu\nu} p^2) + \frac{i}{2}\int d^4x \langle T\, \bar{t}_L \gamma_\mu b_L(0) \bar{b}_L \gamma_\nu t_L(x) \rangle \,, \tag{2.10}$$

where g_2 is the SU(2) coupling constant. For the T-ordered product we again expand in the interaction Lagrangian of Eq. (1.1) and sum the planar bubbles, Fig. 3.

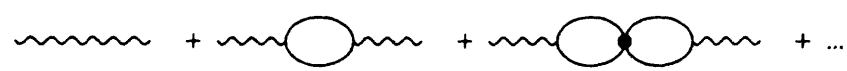


FIG. 3. The planar loops contributing to gauge-boson propagators.

$$\frac{1}{g_2^2} D^W_{\mu\nu}(p)^{-1} = (p_\mu p_\nu / p^2 - g_{\mu\nu}) \left[\frac{1}{\bar{g}_2^2(p^2)} p^2 - \bar{f}^2(p^2) \right] . \tag{2.11}$$

The W-boson mass is the solution to the mass-shell condition

$$M_W^2 = p^2 = \bar{g}_2^2(p^2) \bar{f}^2(p^2) \,, \tag{2.12}$$

while the Fermi constant is the zero-momentum expression

$$\frac{G_F}{\sqrt{2}} = \frac{1}{8\bar{f}^2(0)} \,. \tag{2.13}$$

Nambu became interested too

In the past few years, following the realization that the top quark is heavier than the gauge boson masses, there has been renewed interest [1] in the original Nambu–Jona-Lasinio (NJL) model [2] to provide a possible dynamical symmetry breaking mechanism for the Standard Model. In particular, new strong forces at a high energy scale are assumed to cause the formation of $\bar{t}t$ bound states (top condensation) and dynamically break the $SU(2) \times U(1)$ symmetry. This leads to an effective low energy theory which is qualitatively equivalent to the Standard Model, but with a heavy top quark playing a direct role in the symmetry breaking.

- T. Gherghetta (Nambu student), Regularization of gauged NJL model, 1994

But problems were soon recognized....

$$f_{\pi_t}^2 \simeq \frac{N_c}{16\pi^2} m_t^2 \log \frac{\Lambda^2}{m_t^2}. \tag{3}$$

This relation is often referred to as the Pagels-Stokar formula. In order for the top-quark condensate to account for all of electroweak symmetry breaking, f_{π_t} needs to be equal to $v = 175\,\text{GeV}$. The currently measured top quark mass is $m_t = 175 \pm 6\,\text{GeV}$ [7], which means

---

of m_t and therefore f_{π_t}. The quadratic sensitivity to the condensate scale induces a large hierarchy problem for the weak scale (m_t and f_{π_t}) if Λ is above a few TeV. For large Λ the four-fermion coupling G must be tuned to one part in Λ^2/m_t^2. For a condensate scale in the multi-TeV region, this finetuning is greater than one part in 10^3. It will be assumed here that finetunings much above this are unnatural, and are probably not maintained by nature [8]. Therefore, from the Pagels-Stokar relation the decay constant associated with top-quark condensation is $f_{\pi_t} \lesssim 60\,\text{GeV}$, implying that top-quark condensation is a spectator to electroweak symmetry breaking (EWSB). That is, top-quark condensation mainly

Not to mention the problem of lepton masses!

- JDW, EWSB boson of Top Condensate, `96

Idea still around but pressured by theory and data realities:

<u>Theory</u>: other fermion masses, retaining only top compositiness, finetuning for vev=246 GeV, light Higgs mass prediction (~$2m_t$ more expected), etc.

<u>Data</u>: no deviations in gg->h or h->$\gamma\gamma$ rate (still early though)

Viability still possible with epicycles.

Nevertheless: Is the particle physics Higgs boson "fictitious" as Anderson suggests?

If fictitious means that it is not precisely the Higgs boson of the simple Higgs theory, then I believe it is fictitious!

If fictitious means that it cannot be a fundamental scalar, then I am less sure. (neglecting high-scale quantum gravity scale issues – strings of string theory, etc)

If it is "fictitious" then at least it is "almost a Standard Model Higgs boson"

Left with simple Higgs boson theory. Nevertheless, such a simple theory being the end of the story is hard to believe.

Even our Condensed Matter colleagues must believe we are not done.

Next time you meet C.M. physicist tell him/her:

"The entire universe is a superconductor but we are only in the Ginzburg-Landau stage of understanding!"

They will feel sorry for us.

All lovers of knowledge agree:

We have to know what's behind Higgs boson.

Maybe it's supersymmetry : find the superpartners (not so easy)

Maybe it's composite Higgs ideas : find the evidence (ρ, etc.)

Maybe the effective potential is not simply ϕ^4 : measure it

Maybe it's an idea we haven't thought of : comprehensive exploration of the effective theory and resonances

All reasonable ideas are worth pursuing, and all relevant experiments/colliders worth supporting.

Pursuing signs of "fictitious"

Standard Model Higgs theory has unambiguous predictions for its productions and decays once we know its mass which is known now (125 GeV).

However, its production rates and its probabilities of decaying into various other particles would be slightly different if "fictitious".

$$
\begin{aligned}
Br(H \to bb)_{SM} &= 60\% \\
Br(H \to WW)_{SM} &= 20\% \\
Br(H \to \tau\tau)_{SM} &= 6\% \\
Br(H \to \gamma\gamma)_{SM} &= 0.2\%
\end{aligned}
$$

$$
\begin{aligned}
Br(H \to bb) &= Br(H \to bb)_{SM}\,(1+\epsilon_b) \\
Br(H \to WW) &= Br(H \to WW)_{SM}\,(1+\epsilon_W) \\
Br(H \to \tau\tau) &= Br(H \to \tau\tau)_{SM}\,(1+\epsilon_\tau) \\
Br(H \to \gamma\gamma) &= Br(H \to \gamma\gamma)_{SM}\,(1+\epsilon_\gamma)
\end{aligned}
$$

$\varepsilon \sim v^2/\Lambda^2$ where Λ is

- Compositeness scale, or
- Supersymmetry scale, or
- Size of X-dimensions, or
- Or CFT breaking scale, or

The deviations from these ε's may be only a few percent or less. Will take many years to be sensitive to that, and probably requires another collider (e+e-).

- Gupta, Rzehak, JW, '13

Conclusions

We are born into the Higgs boson era and it's our lot to sort it out. *Copernicus had the solar system, and we have the Higgs boson*.

Next time we discuss in some more detail "alternative" or "more complete" theories of EWSB.

In third lecture we discuss technical issues on precision Higgs and Electroweak analysis needed to help us determine if the Higgs is "fictitious"