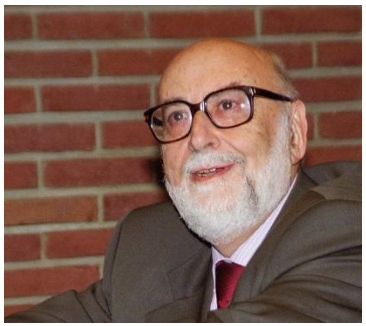
$\vec{B}$

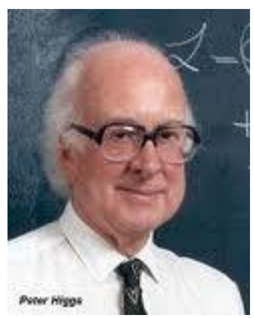
$\vec{E}$

The old question …

Which to use ?

$\vec{H}$ ….




Peter Higgs

	Article	Reception date	Publication date
1	F. Englert and R. Brout Phys. Rev. Letters 13 (1964) 321	26/06/1964	31/08/1964
2	P.W. Higgs Phys. Letters 12 (1964) 132	27/07/1964	15/09/1964
3	P.W. Higgs Phys. Rev. Letters 13 (1964) 508	31/08/1964	19/10/1964
4	G.S. Guralnik, C.R. Hagen and T.W.B. Kibble Phys. Rev. Letters 13 (1964) 585	12/10/1964	16/11/1964

Physics Lett B 12:
failure of NambuGoldstone
in presence of gauge fields


PHYSICAL REVIEW LETTERS
NUMBER 10
PHYSICAL REVIEW LETTERS
BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS
BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS
GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES
PHYSICAL REVIEW LETTERS
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The (almost simultaneous) Brout-Englert and Higgs papers are perfectly complementary,
While Higgs shows at the classical level the disappearance of Goldstone bosons,

Brout and Englert tackle the problem at quantum level (Feynman diagrams)
in what will later be known as a « renormalizable » gauge.
They pave to way to the renormalizability of the theory (although for the non-Abelian case the proofs of ‘t Hooft and Veltman will be needed).

Together, they give the full picture

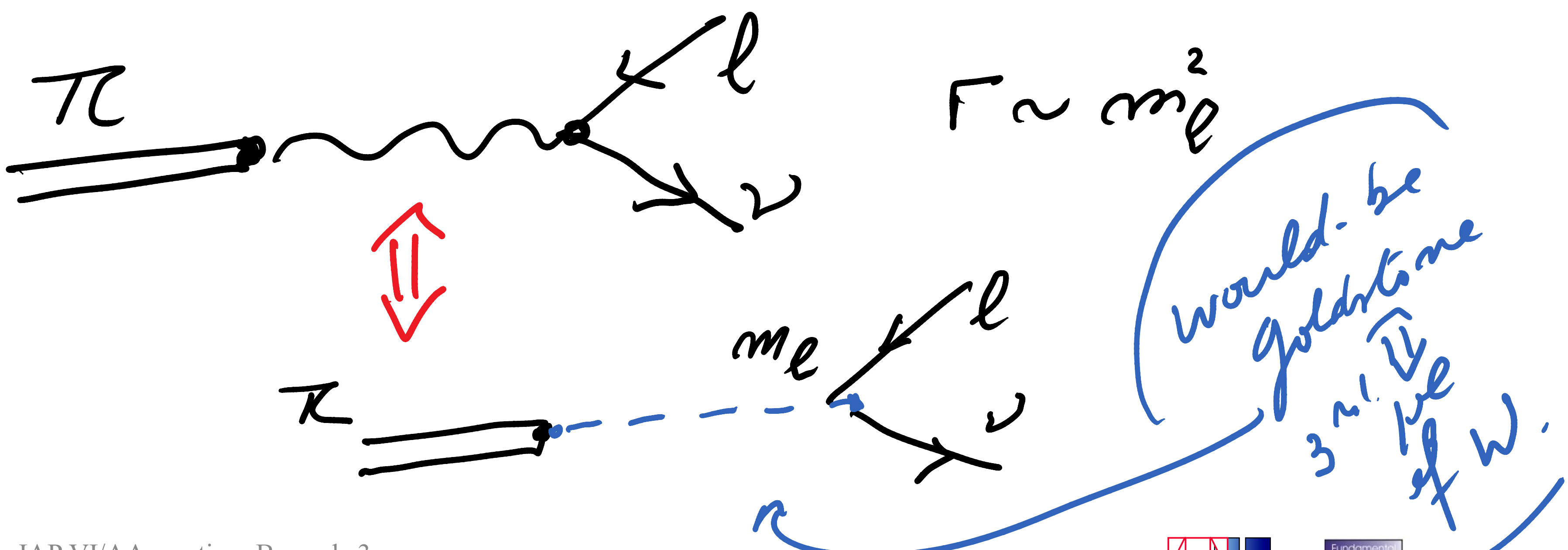
⚠ only on shell!

In fact, it is a standard (and instructive) exercise
for our students to prove the equivalence of the 2 approaches in a scattering process:

The Mechanism or the Boson ?

The mechanism is probably the most important,
It allows for a renormalizable theory of weak interactions,
and is actually well-proven (precision calculations),

Its early manifestation is actually already seen in π decays..



Some like to claim that Brout-Englert → mechanism , while Higgs → Boson
Some even claim that the Scalar boson is hard to find in Brout-Englert paper …

?

Let us look closer …
… we need to go all the way to
Equation 1

ization to an arbitrary compact Lie group.

The interaction between the φ and the A_μ fields is

$$H_{\text{int}} = ieA_\mu \varphi^* \overleftrightarrow{\partial}_\mu \varphi - e^2 \varphi^* \varphi A_\mu A_\mu, \tag{1}$$

where $\varphi = (\varphi_1 + i\varphi_2)/\sqrt{2}$. We shall break the symmetry by fixing $\langle \varphi \rangle \neq 0$ in the vacuum, with the phase chosen for convenience such that

This is the Abelian case, and $\varphi 1$ is « The » Scalar, $\varphi 2$ being absorbed…

Looks familiar ?
From you SM course?

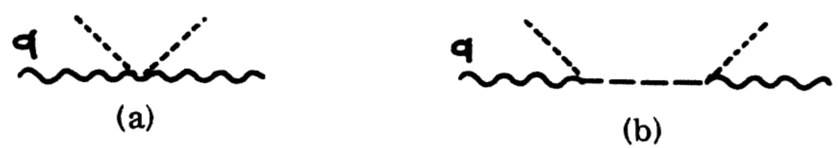


FIG. 1. Broken-symmetry diagram leading to a mass for the gauge field. Short-dashed line, $\langle \varphi_1 \rangle$; long-dashed line, φ_2 propagator; wavy line, A_μ propagator. (a) $\to (2\pi)^4 ie^2 g_{\mu\nu} \langle \varphi_1 \rangle^2$, (b) $\to -(2\pi)^4 ie^2 (q_\mu q_\nu / q^2) \times \langle \varphi_1 \rangle^2$.

Now that we have found the Scalar particle in Eq. 1, *it is still possible to argue it should be named otherwise ….*

- Higgs pointed out a massive scalar boson

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

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0{}^2)\}^{1/2}$

- ” “… an essential feature of [this] type of theory … is the prediction of incomplete multiplets of vector and scalar bosons
- Englert, Brout, Guralnik, Hagen & Kibble did not comment on its existence

(from John Ellis’s talk in *Higgs Hunting 2011*)

(interesting comparison : the P-Q axion …)

In fact, this potential / mass issue was well-known
….. For example , Goldstone

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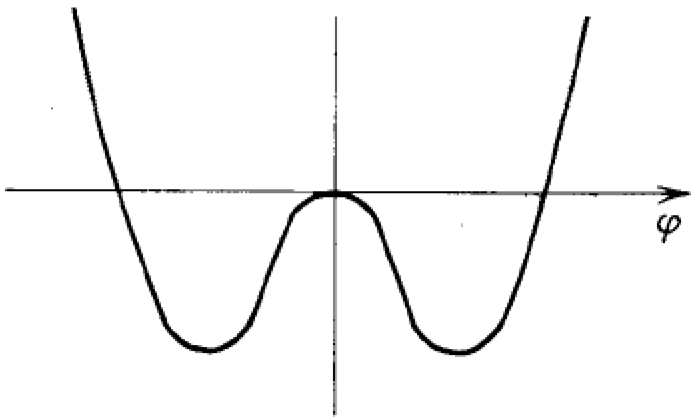


Fig. 7.

$$\frac{\mu_0^2}{2}\varphi^2+\frac{\lambda_0}{24}\varphi^4\,,$$

is as shown in Fig. 7.

The classical equations

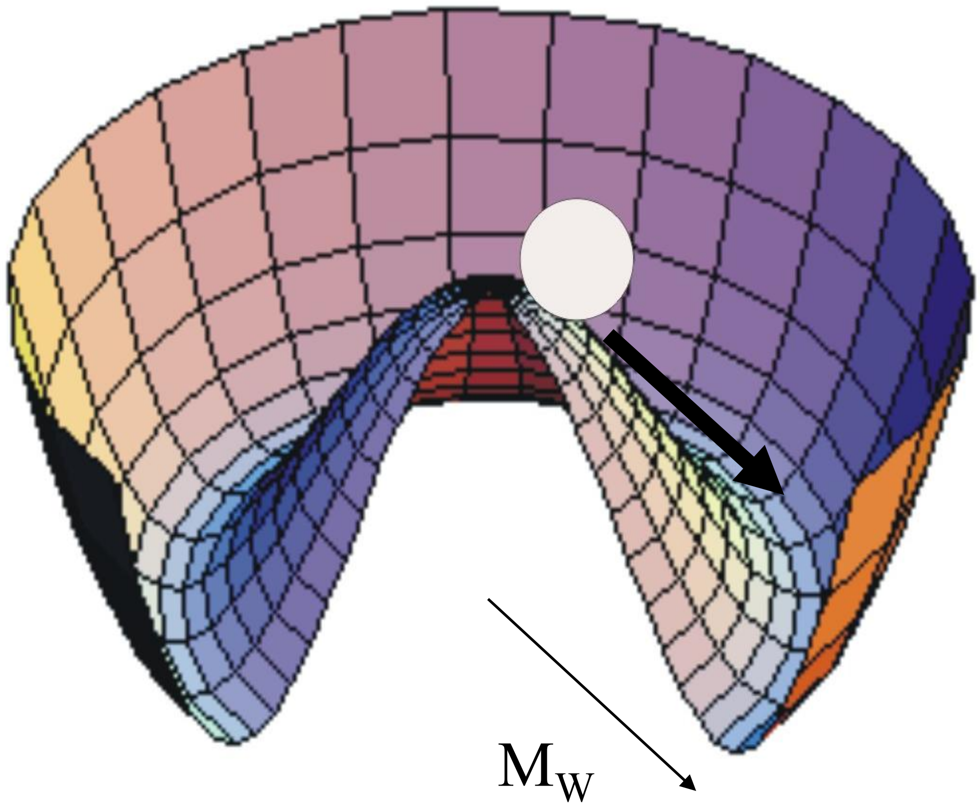
$$(\Box^2+\mu_0^2)\varphi+\frac{\lambda_0}{6}\varphi^3=0\,,$$

now have solutions $\varphi=\pm\sqrt{-6\mu_0^2/\lambda_0}$ corresponding to the minima of this curve. Infinitesimal oscillations round one of these minima obey the equation

$$(\Box^2-2\mu_0^2)\,\delta\varphi=0\,.$$

These can now be quantized to represent particles of mass $\sqrt{-2\mu_0^2}$. This is simply done by making the transformation $\varphi=\varphi'+\chi$

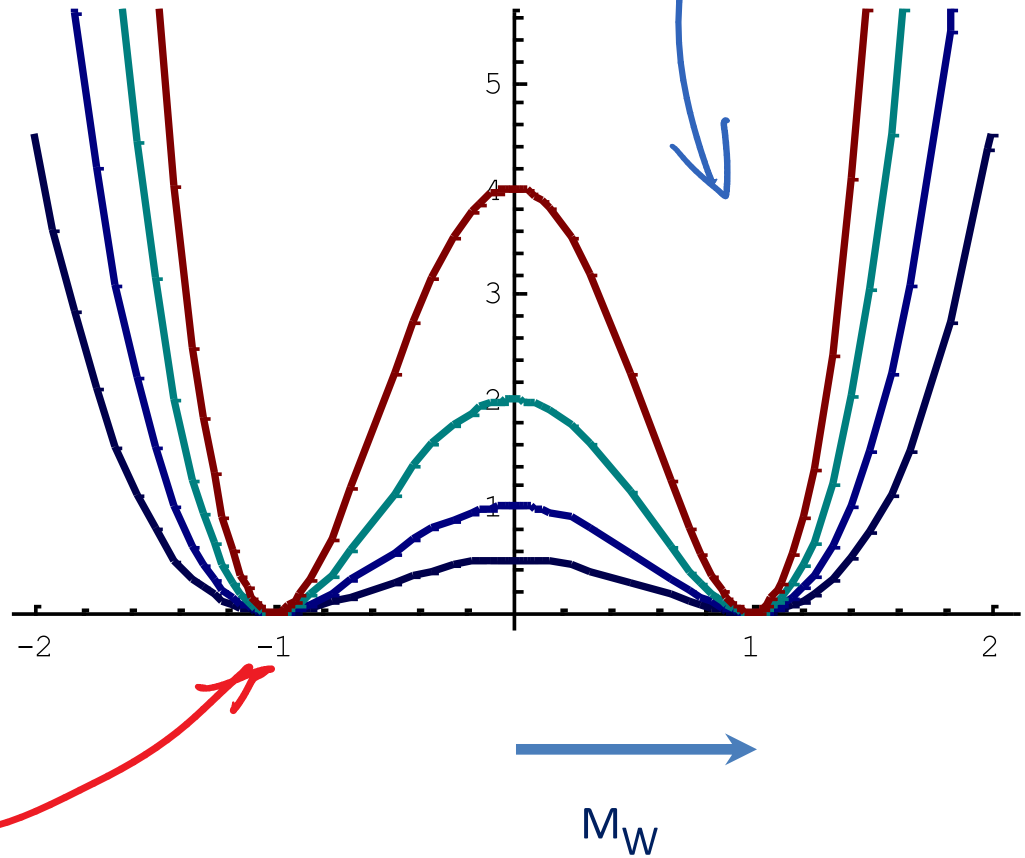
About the Mass of the Scalar Boson…



About the Mass

Shape unknown

min ⟷ μ_W



curvature

$\sim m^2_{scalar}$

Both Brout-Englert and Higgs deal with the

- Abelian case
- Non-Abelian case
- « Dynamical » situation:
  the scalar bosons (including the would-be Goldstone) can be either « fundamental » , or « composite » (like what is now called Technicolor)

*In the latter case, the scalars (goldstone and physical) could be compared to the pion and **sigma** of QCD ….*

Remember however that they were in a « generic » symmetry breaking situtation, thinking also of a way to explain the unseen force of strong interactions, so the pheno can be quite different …

A quote from GHK,
About their remaining scalar (masslesss in their case ….)

part. The two degrees of freedom of A_k^- 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,

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and has nothing to do with the Goldstone theorem.

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was partially solved by Englert and Brout,[5] and bears some resemblance to the classical theory of Higgs.[6] Our starting point is the ordinary electrodynamics of massless spin-zero particles, characterized by the Lagrangian

$$\mathcal{L} = -\tfrac{1}{2}F^{\mu\nu}(\partial_\mu A_\nu - \partial_\nu A_\mu) + \tfrac{1}{4}F^{\mu\nu}F_{\mu\nu} + \varphi^\mu \partial_\mu \varphi + \tfrac{1}{2}\varphi^\mu \varphi_\mu + ie_0 \varphi^\mu q \varphi A_\mu,$$

Gauge bosons vs Fermion masses ….

It is absolutely obvious that the initial goal of the symmetry breaking mechanism in Brout-Englert paper was to allow for Vector (gauge) boson masses; by « power counting » this seems feasible without destroying renormalizability. (this is correct, but the ren. of the non-Abelian case will need ‘t Hooft, Veltman, Faddeev-Popov …

Quite interestingly, in the Physics Lett B paper, Higgs centers on getting rid of (unwanted) Goldstone bosons in a Nambu-Goldstone symmetry breaking framework, the gauge bosons appear first as tools for this purpose – until the mechanism is fully detailed (in classical form) in PRL, with an explicit demonstration of the disappearance of the Goldstone, but no indication of renormalizability…

What about fermion masses ?

What about fermion masses ?

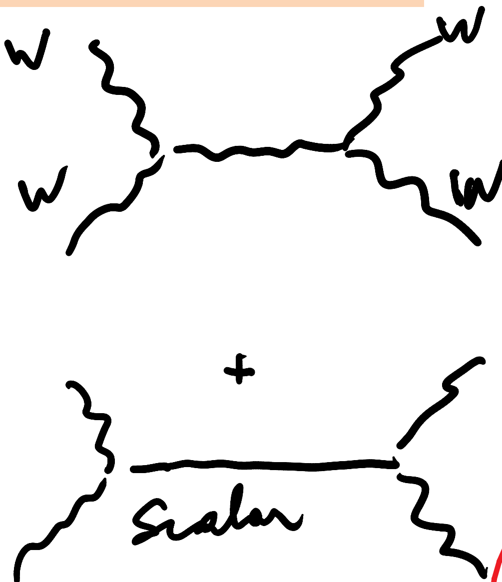
The bulk of the nucleon masses does not come from the SM breaking…
… but rather from chiral symmetry breaking through confinement, with the pion as a pseudo-Goldstone boson … and no vector mass resulting.

In the current context of the SM, where chiral fermions play a central rôle and only the L-part of SU(2) is gauged,
the symmetry breaking mechanism (and the Brout-Englert-Higgs boson) is necessary ALSO for quark and lepton masses (this is actually often used as a pedagogical argument to introduce symmetry breaking)

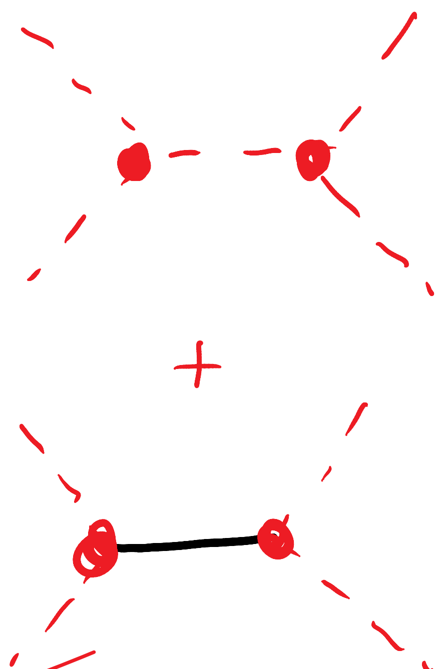
Is the scalar absolutely needed ?

At the difference of Goldstone boson, difficult to prove from first principles, except in «elementary particle » case – what if composite ?

Unitarity argument ?



W long. →



argument fails if "soft" vertices.

needed for unitarity ?