
Air Mail
90P
2010
Dr Eilam Gross
Particle Physics Department
Weizmann Institute of Science
76100 Rehovoth
ISRAEL
FROM
Peter Higgs
2 Darnaway Street
Edinburgh EH3 6BG

Higgs (in a snail mail to me):

History of SSB

(1) Order of contributions:–

1. Nambu (1960), Nambu & Jona-Lasinio (1961)
2. Goldstone (1961)
3. Goldstone, Salam & Weinberg (1962)
4. Anderson (1963)
5. Englert & Brout (Aug. 1964)
6. Higgs (Sep. & Oct 1964)
7. Guralnik, Hagen & Kibble (Nov. 1964)

See the enclosed reprint for my account of papers 1 to 6.

Guralnik, Hagen & Kibble (7) showed how the Goldstone theorem is evaded in a simple linear model. Note that all six of us were awarded the 2010 Sakurai Prize by the APS.

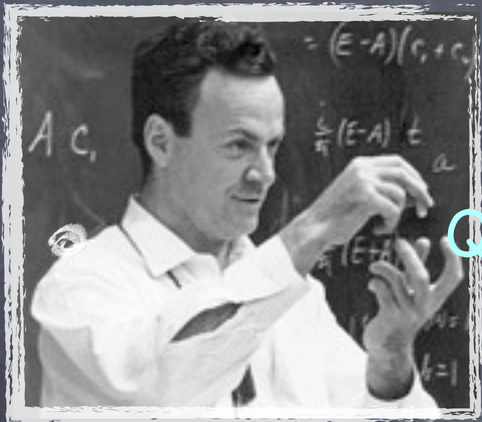
Higgs (in a snail mail to me):

Landau (1960)
Goldstone(1961)
Goldstone, Salam , Weiberg (1962)
Anderson (1963)
Englert & Brout (1964)
Higgs (1964)
Geralnik, Hagen & Kibble (1964)

Note that all six of us were awarded the 2010 Sakuarai Prize of the APS

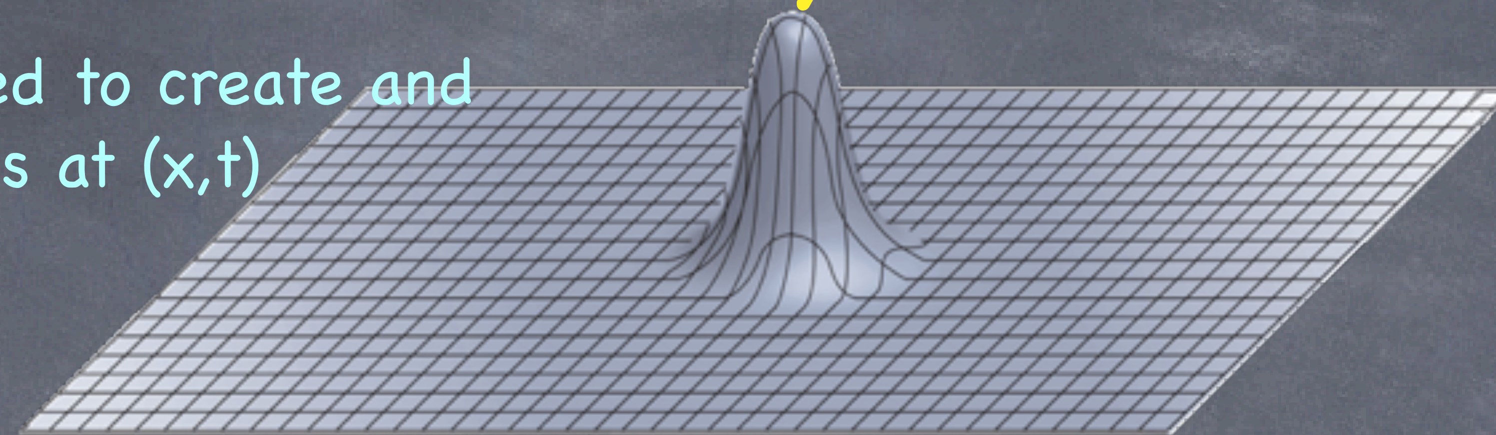
# A Prelude to the Nobel Prize

- **2010 Sakurai Prize awarded for 1964 Higgs Boson theory work to Hagen, Guralnik, Kibble, Brout, Englert & Higgs**



# (QED) Field Theory

- Quantum fields are used to create and annihilate particles at (x,t)

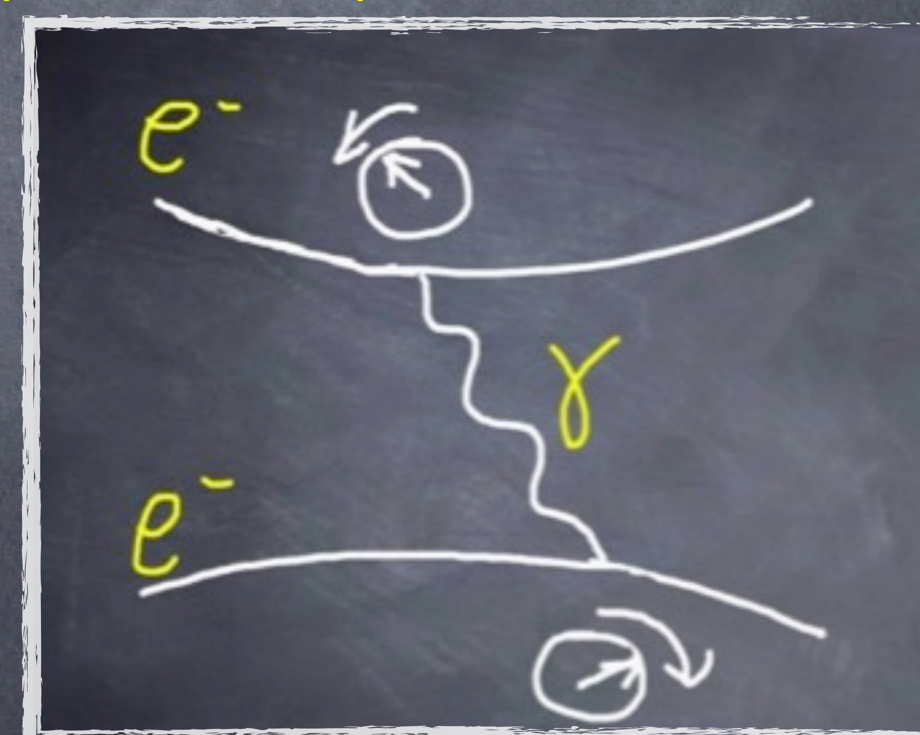


- QED was developed in the first half of the 20th century to describe the interaction of matter with light (photons and electrons)
- QED is based on the phase U(1) symmetry (which ensures conservation of electric charge).

$$\bar{\psi}\gamma^{\mu} D_{\mu}\psi = \bar{\psi}\gamma^{\mu}\partial_{\mu}\psi + ie\bar{\psi}\gamma^{\mu}A_{\mu}\psi$$

$$\psi \to e^{ie\theta(x,t)}\psi$$

- The photon is the guardian of the local gauge symmetry.
- The symmetry requires that the photon be massless.
- The symmetry ensures the renormalizability of the theory, the theory is free of infinities (i.e. the theory "does not predict particles doing things more often than always")



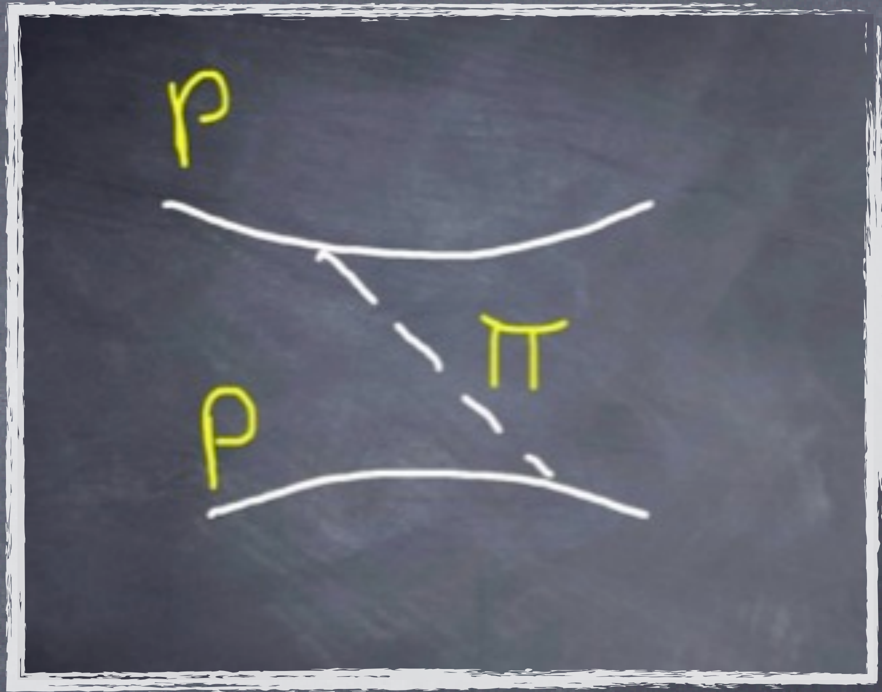
# (QED) Field Theory

- Attempts to describe the nuclear interactions (p-p, p-n, n-n) in a similar way to QED via local symmetries (SU(2) Yang-Mills) failed.

- The range of the nuclear force is short and massless force mediators (a-la QED photons)-> infinite range

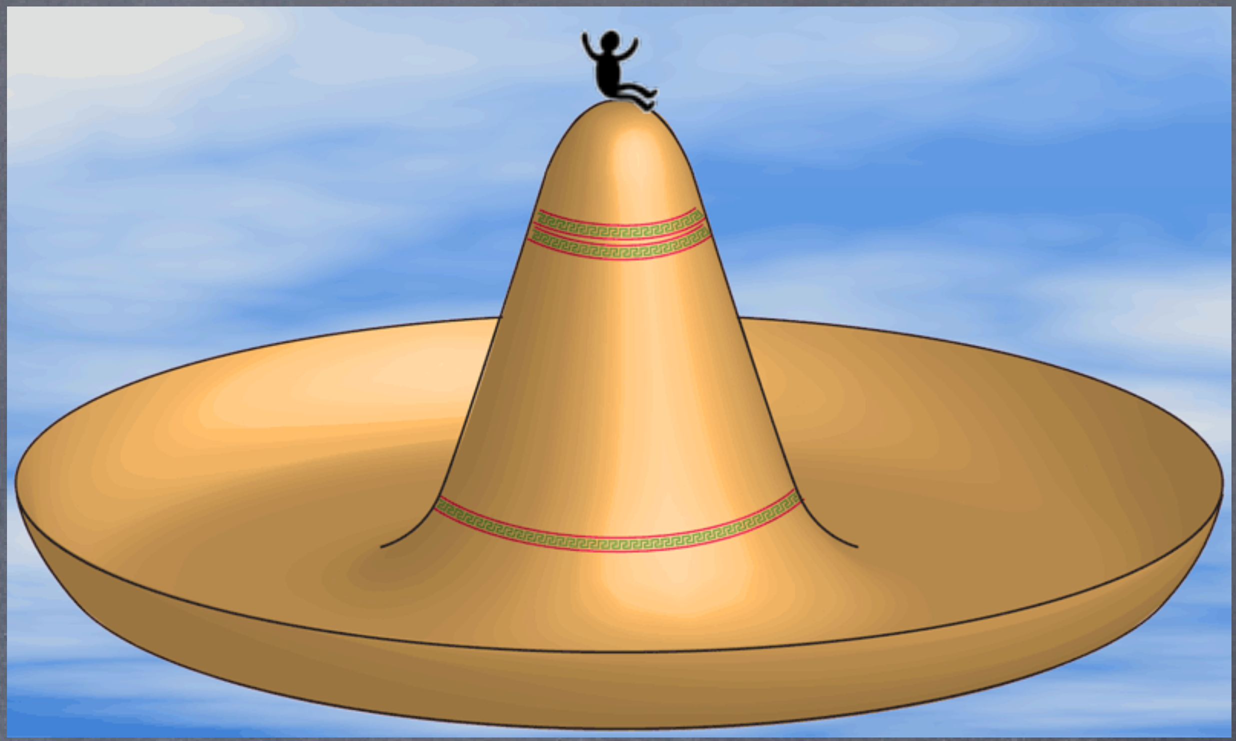
- The nuclear force is short range - the mediating particle must be massive. Is it the pion?

- Perhaps the symmetry is spontaneously broken allowing a massive pion (???)



# Spontaneous Symmetry Breaking

- Spontaneously Symmetry Breaking was first introduced by Ginzburg & Landau (1950,1957)
(in an attempt to explain superconductivity)



- The physics of the system (Lagrangian) posses some exact symmetry, but the vacuum (ground state) breaks this symmetry

- Nambu (1960) proposed for the first time that SSB is the source of fermion masses in elementary particle physics:
"the existence of such a condensate (scalar field) would break the symmetry of the model.... . In particle physics, that would be a non-Abelian group containing the U(1) group associated with electric charge conservation as a subgroup"

# Spontaneous Symmetry Breaking

- Inspired by Nambu, Goldstone (1961) studies models featuring scalar fields and finds that all these models contain (under SSB) massless (Nambu-Goldstone) Bosons

- Goldstone, Salam and Weinberg (1962) prove formally that Goldstone Bosons must occur whenever a symmetry *("like isospin or strangeness")* is broken (Goldstone Theorem). But no such Bosons were observed experimentally.

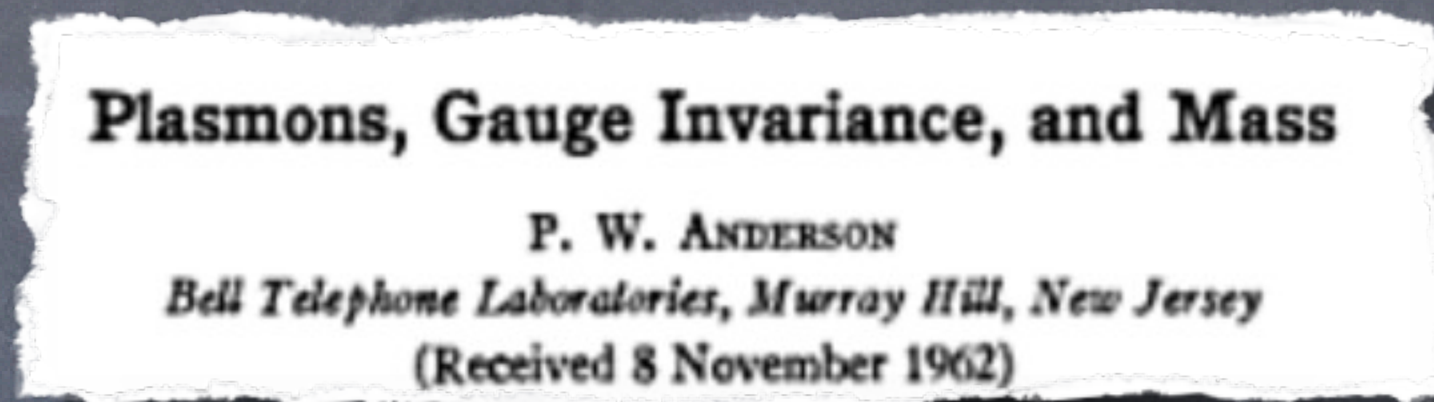
- Weinberg recalls in his Nobel lecture (1979) that he was so disappointed that he added a quote to the paper from king Lear: *"Nothing will come out of nothing, speak again"*

- Is Quantum Field Theory a one trick pony? Can it explain only long range interactions?

# Spontaneous Symmetry Breaking

Philip Anderson (1963) points out that in a superconductor the Goldstone mode becomes a massive plasmon-mode, due to its electromagnetic interaction.

Physics Review
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 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."**

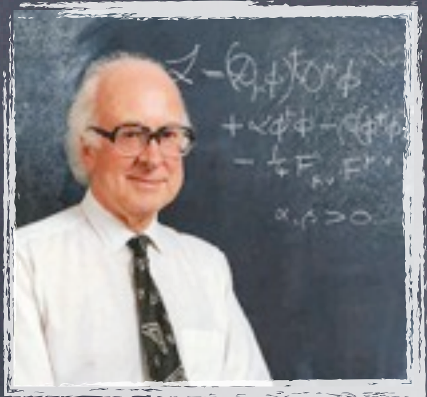
# Spontaneous Symmetry Breaking

The first of Polyakov's papers, "Spontaneous symmetry breaking of strong interaction and absence of massless particles", was written with Alexander Migdal in early 1964.

The two theorists, both 19 at the time, had essentially discovered what later became known as the Higgs mechanism.

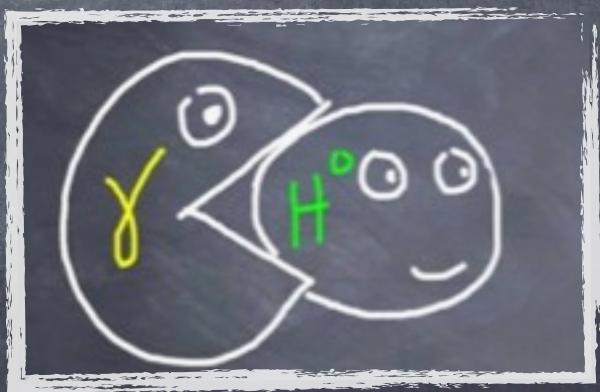
- Owing to several unfortunate circumstances, this Migdal-Polyakov paper was published in the Journal of Experimental and Theoretical Physics only in 1966, two years after it had been completed.

# Spontaneous Symmetry Breaking



Peter Higgs (Phys. Lett. July 1964) shows that one can evade Goldstone theorem. He shows that if the broken symmetry is local gauge symmetry (like electromagnetic U(1) gauge invariance), then, although the Goldstone Bosons exist formally, and in some sense real, they can be eliminated by gauge transformation, so that they do not appear as physical particles. That explains why experiment fails to detect the massless Bosons.

- The missing Gloldstone boson appears instead as helicity zero state of the massless boson which thereby acquire a mass.
- The massless boson eats the Goldstone Boson and acquires mass.



# The Higgs Mechanism

- Based on field theory (using a lagrangian formalism) Higgs develops the formalism of the mechanism by which the Goldstone Boson is "eaten" by the photon and the pohoton becomes massive -> short range interaction

- He sends the 3 pages paper to Physics Letter, the paper is rejected. Higgs: "I was rather shocked. I did not see why they would accept a paper that said this is a possible way to evade the Goldstone theorem, and then reject a paper that showed how you actually do it."

- Higgs adds an epilogue to the paper: "it is worth noting that an essential feature of this type of theory is the prediction of incomplete multiplets of scalar and vector bosons" and sends the revised version to PRL.

# The Higgs Mechanism

- Higgs: "The referee who, I discovered later, was Nambu, drew my attention to a paper by Englert and Brout that they had just published in Physical Review Letters". Higgs is asked to cite Englert & Brout and the paper is accepted (August 1964)

- Guralnik, Hagen and Kibble (1964).
  Guralnik (2009): "As we were literally placing the manuscript in the envelope to be sent to PRL, Kibble came into the office bearing two papers by Higgs and the one by Englert and Brout. These had just arrived in the then very slow and unreliable... Imperial College mail. We were very surprised and even amazed."

# The Higgs Mechanism

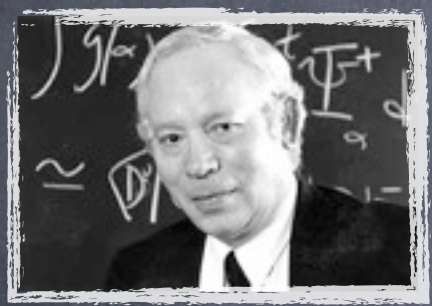
- Higgs (in a snail mail to me):

My first paper outlined how to evade the Goldstone theorem.
Englert & Brout showed how a gauge field interaction turns Goldstone massless spin-0 bosons (elementary <u>or</u> composite) into helicity-0 states of massive spin-1 particles.
They ~~[illegible]~~ started from Feynman diagrams and didn't discuss the remaining massive spin-0 particles.
In my second paper I used Lagrangian field theory explicitly with elementary scalar fields (à la Goldstone) coupled to a gauge field, so the massive spin-0 boson was an obvious feature, to which I drew attention.
All three of us tried without success

# The Higgs Mechanism

- Higgs (in a snail mail to me):
  In my first paper I outlined how to evade the Goldstone theorem.
  Englert & Brout showed how a gauge field interaction turns Goldstone massless bosons (elementary OR composite) into helicity-0 states of massive spin-1 particles. They started from Feynmann diagrams and didn't discuss the remaining massive spin-0 particles.
  In my second paper I used Lagarangian field theory explicitly with elementary scalar fields (a` la Goldstone) coupled to a gauge field, so the massive spin-0 boson was an obvious feature, to which I drew attention.

# The Birth of the Standard Model

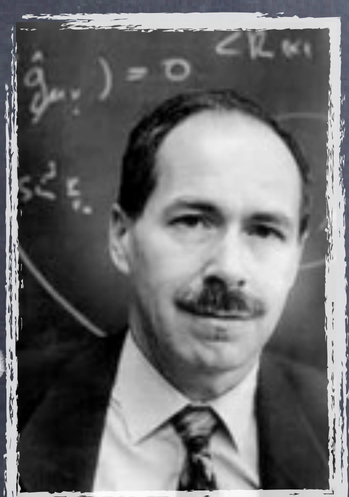
-  Glashow (1961) suggests that the symmetry of the Electro-Weak interaction is SU(2)xU(1) and is broken to U(1) em. But Glashow puts the masses of the force carriers by hand and his theory is therefore non-renormalizable
-  Weinberg (1967) implements Higgs mechanism to Glashow's SU(2)xU(1) and writes the most quoted paper in the history of particle phsyics

  (almost most quoted . .... >7500 citations).
- Weinberg predicts that the mass of the weak interaction force carriers is mW=80 GeV and mZ=90 GeV, but it took another 14 years to confirm it experimentally.

# The Birth of the Standard Model

wrong.

Is this model renormalizable? We usually do not expect non-Abelian gauge theories to be renormalizable if the vector-meson mass is not zero, but our $Z_\mu$ and $W_\mu$ mesons get their mass from the spontaneous breaking of the symmetry, not from a mass term put in at the beginning. Indeed, the model Lagrangian we start from is probably renormalizable, so the question is whether this renormalizability is lost in the reordering of the perturbation theory implied by our redefinition of the fields.



- The (theoretical) story was completed when ‘tHooft (& Veltman) proved the renormalizability of Yang-Mills theories with masses generated by spontaneous symmetry breaking in a scalar field system in 1971.

- All that is left is to find the mass generator, the Higgs Boson