Introduction to Higgs Physics (in 3 lessons)

J. Lorenzo Diaz Cruz

FCFM-BUAP (Puebla, Mexico)

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1. Introduction to Higgs Physics

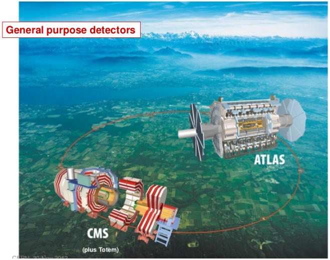
- The origins - QFT, QED, YM, NG, BEH (Theory)
- The Standard Model - GSW (Model Building)
- SM Higgs sector - WXYZ (Phenomenology)
- Higgs search at the LHC- (a,b,c,d,.... w,x,y,z) (Experimental)
- Higgs physics beyond the SM - (THDM, MSSM, NHDM)
- Implications of Higgs physics in the far UV -

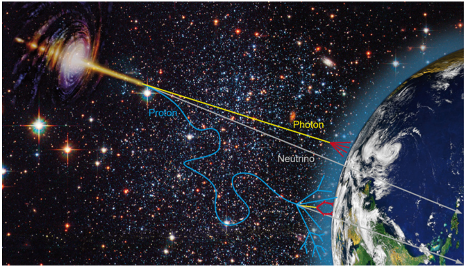
Some references

1. Popular: Veltman, t Hoft, "The second creation", ..
2. Basic: Kane, Cottingham,..
3. Advanced: Cheng and Li, TD Lee,
4. QFT: Ryder, Peskin, Sredniky/Schwartz, Weinberg,
5. Phenomenology: Varger and Philips, Branco et al.
6. Historic perspective: J. Wells, arXiv:1609.04268 [hep-ph]
   "The theoretical physics ecosystem behind the discovery of the Higgs boson "
   "...the higgs boson could had not been discovered by accident"

Tools to explore the micro and macro cosmos

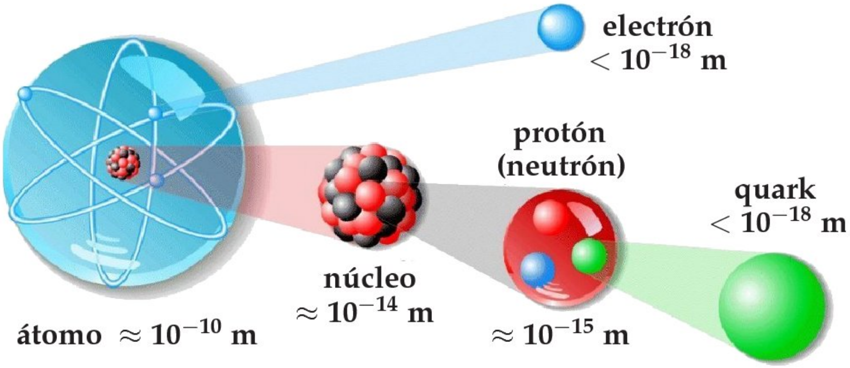
- Energy frontier
- Intensity frontier
- Cosmic frontier

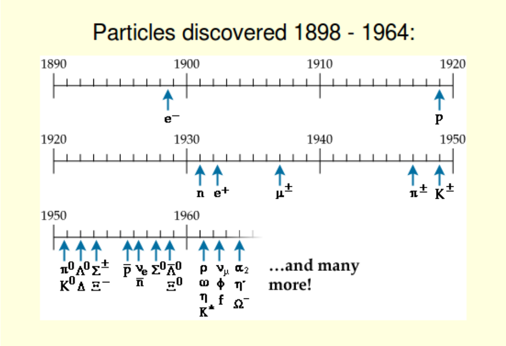


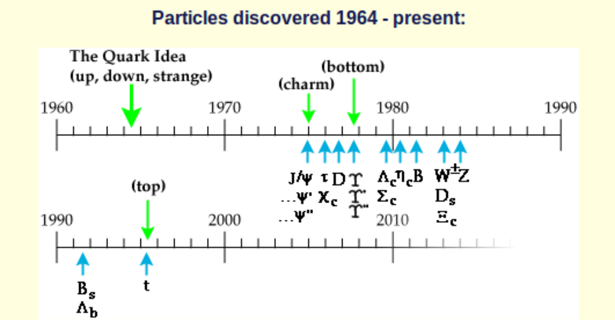


Cultural impact of Particle Physics

The structure of matter




Particles discovered 1898 - 1964:
1890
1900
1910
1920
e⁻
p
1920
1930
1940
1950
n
e⁺
μ±
π±
K±
1950
1960
...and many more!


Particles discovered 1964 - present:
The Quark Idea
(up, down, strange)
(charm)
(bottom)
1960
1970
1980
1990
J/ψ
τ
D
ϒ
B
W±Z
(top)
1990
2000
2010
t

Important parameters:

- $m_e = 0.511$ MeV, $m_\mu = 105$ MeV, $m_\tau = 1700$ MeV,

- $m_u = 5$ MeV, $m_d = 10$ MeV, $m_s = 150$ MeV,
- $m_c = 1.5$ GeV, $m_b = 4.5$ GeV, $m_t = 173$ GeV,

- $m_p = 938.272$ MeV, $m_n = 939.565$ MeV,

  $m_{\pi^+} = 139.57$ MeV, $m_{\pi^0} = 134.98$ MeV, $m_\rho = 770$ MeV,

- $m_W = 80$ GeV, $m_Z = 90$ GeV, $m_h = 125 - 126$ GeV,

- $\alpha_{em} = 1/137$, $\sin^2\theta_W = 0.23$, $\alpha_s = 0.111$,

- $m_e =$? , $m_\mu =$? , $m_\tau =$? ,
- $m_u =$? , $m_d =$? , $m_s =$? ,
- $m_c =$? , $m_b =$? , $m_t =$? ,
- $m_p =$? $m_n =$? ,

  $m_\pi =$? , $m_\rho =$? ,
- $m_W =$? , $m_Z =$? , $m_h =$? ,
- $\alpha_{em} =$?, $\sin^2\theta_W =$?, $\alpha_s =$?,

Why is it important to know these numbers?

One of our goals is to find a natural order of the world, and it helps to have an estimate of the dominat effects that describe a given phenomena ($\rightarrow$ Effective Theories) ,

- How the decays go?
  $p \rightarrow n + e + \nu_e$ or $n \rightarrow p + e + \nu_e$?
  $\pi \rightarrow \mu + \nu$ or $\mu \rightarrow \pi + \nu$?
- Why $\tau(\pi^+) = 2.6 \times 10^{-8}$ sec. vs. $\tau(\pi^0) = 8.4 \times 10^{-17}$
- Which interaction is most relevant?
- Why the Higgs was searched in *pp* collisions at high energies? (LHC)
- Where does the proton mass comes from?

Homework:
1) Learn by hearth these numbers.

Quantum Field Theory (QFT)

- The sub-atomic wrld is described with Quantum Mechanics and Special Relativity,
- A first step to combine them was due to Dirac → prediction of anti-particles,

$$L_{KG} = \partial^\mu \phi \partial_\mu \phi - m^2 \phi^2 \to (\partial^\mu \partial_\mu + m^2)\phi = 0 \quad (1)$$

$$L_{Dirac} = \bar{\Psi}(i\gamma^\mu \partial_\mu - m)\Psi \to (i\gamma^\mu \partial_\mu - m)\Psi = 0 \quad (2)$$

- Relativistic Quantum Mechanics → QFT,
- First formulation of QFT was due to Heisenberg, Jordan y Pauli,
- Lorentz Transformations:

$$x^\mu \to x'^\mu = \Lambda^\mu_\nu x^\nu \quad (3)$$

$\Lambda^\mu_\rho \Lambda^\nu_\sigma g_{\mu\nu} = g_{\rho\sigma} \to$ Lorentz Group: $SU(2) \times SU(2)$

Quantum Field Theory

To define QFT:

- Classical fields = Irreps. of Lorentz group [$\simeq (j, j')$]
- Cuantization (old): Canonical Formalism, Path-integrals, Diagramar (MV...)
- Poincare Group/Wigner work (See Weiberg treatice on QFT): Massive particles: Objects with spin ($s = 0, \frac{1}{2}, 1, ...2$) and mass, Massless particles: Objects with helicity ($h = 0, \pm\frac{1}{2}, ...$),
- Solution to the theory: S-matrix (Pert. $\rightarrow$ Feynman), Non-pert. (Lattice), ...
- Quantum Electrodynmics (QED) was the first achievement of QFT,
- Gauge invariance is a key concept in the formulation of QED,
- Problem: To 2do order (loop diagrams) give infinity,
- Consistent treatment of infinities in QED (Renormalizacion) $\rightarrow$ Nobel prize to Feynman, Schwinger and Tomonaga.

Gauge Principle :

Invariance under phase transformations can be studied within Non-relativistic Quantum Mechanics,

- Probability ($\Psi^\dagger\Psi$) is invariant under changes of phase (=cte):

$$\Psi \to \Psi' = e^{i\alpha}\Psi, \tag{4}$$

- Schroedinger equation

$$ih\frac{\partial\Psi}{\partial t} = -\frac{h^2}{2m}\Delta\Psi, \tag{5}$$

is not invariant if $\alpha = \alpha(t, x_i)$

- $\partial_i(e^{i\alpha}\Psi) = e^{i\alpha}\partial_i\Psi + e^{i\alpha}(i\partial_i\alpha)\Psi$

Invariance and interactions:

(Sustitucion Minima)

- $\frac{\partial}{\partial t} \to \frac{\partial}{\partial t} - eV = D_t, \quad \partial_i \to \partial_i - eA_i = D_i,$
- Where: $V \to V - \frac{\partial \alpha}{\partial t}, \quad A_i \to A_i - \partial_i \alpha,$
- Schrodinger equation with EM interaction is:

$$ihD_t\Psi = -\frac{h^2}{2m}(D_i)^2\Psi, \tag{6}$$

- Local phase transf. $\to$ Abelian Lie Grups $(G = U(1))$

  ex. $U(1) \simeq SO(2)$: Rots. around 1 axis $[R(\theta)]$,
  $R(\theta_1) \times R(\theta_2) = R(\theta_2) \times R(\theta_1),$
- Relativistic Generalization $\to$ Dirac Equation,
- Generalization with Non-abelian groups $\to$ Yang-Mills Theories,

Generalizacion Relativista $\rightarrow$

Abelian gauge theories – QED

free fermion field ψ (for $e^{\pm}$), described by Lagrangian

$$\mathcal{L}_0 = \overline{\psi}\,(i\gamma^\mu \partial_\mu - m)\,\psi$$

- $\mathcal{L}_0$ is invariant under global transformations

  $$\psi(x) \rightarrow \psi'(x) = e^{i\alpha}\,\psi(x) \quad \textit{with } \alpha \textit{ real, arbitrary}$$

  group: $U(1)$, global $U(1)$

  global gauge symmetry

- $\mathcal{L}_0$ is not invariant under local transformations

  $$\psi(x) \rightarrow \psi'(x) = \underbrace{e^{i\alpha(x)}}_{U(x)}\psi(x)$$

- invariance is obtained by "minimal substitution"

$$\partial_\mu \to D_\mu = \partial_\mu - ieA_\mu \qquad \textit{covariant derivative}$$

under the combined transformations

$$\psi(x) \to \psi'(x) = e^{i\alpha(x)}\,\psi(x) \equiv U(x)\,\psi(x)$$
$$A_\mu(x) \to A'_\mu(x) = A_\mu(x) + \tfrac{1}{e}\,\partial_\mu\alpha(x)$$

local gauge transformations

- group: local $U(1)$, Abelian: $e^{i\alpha_1}e^{i\alpha_2} = e^{i\alpha_2}e^{i\alpha_1}$

basic property: $\boxed{D'_\mu\psi' = U(x)D_\mu\psi}$

$$(\partial_\mu - ieA'_\mu)\,U(x)\psi(x) = U(x)\,(\partial_\mu - ieA_\mu)\,\psi$$

covariant derivative transforms as the fields themselves !!

→ Gauge Principle: Interactions are associated with symmetries!

(QED is an Abelian Gauge Theory)

QED is a Quantum Field Theory (QFT)

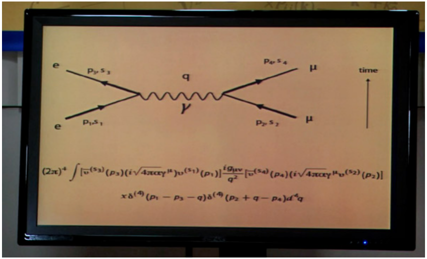
- We use a perturbative language to identify particles,
- S-Matrix (LSZ) $\rightarrow$ Feynman rules $\rightarrow$ Physical Process,
- Amplitud $= \sum$ (Feynman Diagrams)
- Diagramm = Ext. Lines + Int. Lines (Propagators) + Vertices

ex. Scalar Propagator: $\frac{i}{p^2 - M^2 + i\epsilon}$ QED-vertex: $-ie\gamma_\mu$

QED has been proved with a high precision e.g. $a_f = \frac{1}{2}(g-2)$,

$$a_\mu^{th} = (1\,159\,652\,157 \pm 28) \times 10^{-12},$$
$$a_\mu^{exp} = (1\,159\,652\,188 \pm 4) \times 10^{-12},$$

Estimate $e^+e^- \to \mu^+\mu^-$



Non-Abelian gauge theories

- Generalization: "phase" transformations that do not commute

$$\psi \to \psi' = U\psi \quad \textit{with} \quad U_1 U_2 \neq U_2 U_1$$

requires matrices, *i.e.* ψ is a multiplet

$$\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \vdots \\ \psi_n \end{pmatrix}, \qquad U = n \times n \textit{ -matrix}$$

$U \in SU(n), SO(n), ...$
(any classic Lie group)

each $\psi_k = \psi_k(x)$ is a Dirac spinor

$U(\theta_i) = exp(i\theta_i \frac{T_i}{2})$, $\quad T_i$= Generators of Lie algebra,

- similar for **scalar fields:**

$$\phi \to \phi' = U\phi, \qquad \phi = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \vdots \\ \phi_n \end{pmatrix} \qquad \phi^\dagger = (\phi_1^\dagger, \cdots, \phi_n^\dagger)$$

- **group $SU(n)$** $\quad U\,U^\dagger = 1\,,\ \det U = +1$

examples:

$$SU(2): \quad \psi = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} \quad e.g. \quad \psi = \begin{pmatrix} \psi_\nu \\ \psi_e \end{pmatrix}$$ weak *isospin* (or Heisenberg's)

$$SU(3): \quad \psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{pmatrix} \quad e.g. \quad \psi = \begin{pmatrix} \psi_r \\ \psi_g \\ \psi_b \end{pmatrix}$$ *colour*

Non-Abelian LOCAL gauge symmetry

- now: $\theta_a = \theta_a(x)$ for $a = 1, \ldots N$

  (local spacetime functions)

- covariant derivative $\partial_\mu \to D_\mu = \partial_\mu - ig\,\mathbf{W}_\mu$ ($\mathbb{1}\,\partial_\mu$)

- vector field $\mathbf{W}_\mu$ is $n \times n$ matrix: $\mathbf{W}_\mu(x) = T_a W^a_\mu(x)$

- induces interaction term $\mathcal{L}_0 \to \mathcal{L}_0 + \mathcal{L}_{\rm int}$

  with $\mathcal{L}_{\rm int} = g\,\overline{\Psi}\gamma^\mu \mathbf{W}_\mu \Psi = g\,\overline{\Psi}\gamma^\mu T_a \Psi\, W^a_\mu$

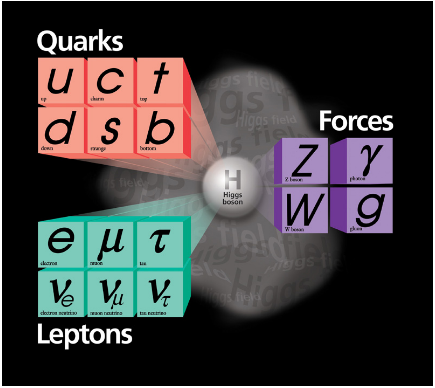
Gauge Principle: There exists a force mediator ("photon") for each generator,

No. of Generators for $SU(N) \to N^2 - 1$

2. THE Standard Model -

The Standard Model (SM)

- Matter consists of quarks and leptones,
- Forces are associated with gauge symmetries,
- Mass arises with spontaneous symmetry breaking,



The (partial) Electro-Weak (EW) unification

- From Fermi Theory(1934) of beta decay ($n \rightarrow p + e + \bar{\nu_e}$), we got to the $V - A$ structure of EW interactions,
- Then to the IVB theory, which propossed a charged IVB ($W^{\pm}$),
- The unification of E.M. and Weak interactions, was suggested by J. Schwinger to S.L. Glashow (1961), who used Yang-Mills theories(1954), with a Lie Group: $G = SU(2)_L \times U(1)_Y$,
- $SU(2)_L \rightarrow$ 2 charged gauge bosons ($W^{\pm}$) + 1 neutral boson (W_3), $U(1)_Y \rightarrow$ 1 neutral boson (B).
- The neutral bosons W_3 y B mix $\rightarrow$ Photon (A) and Z, which was a prediction of the model,
- LH (RH) fermions appear as doublets (singlets) under $SU(2)_L$,

But all particles in this Pre-SM were massless! (contrary to observations)

Renormalization, quarks and QCD

- In 1970-72, t Hooft y Veltman proved that YM theories with SSB were as good as QED (renormalizable and unitary)
- In 1970-73 quarks were incorporated to the SM (GIM),
- Quark model of (Gell-Mann) needed a new quantum number (COLOR),
- Strong interactions were described by a gauge theory $SU(3)_c \rightarrow 8$ gluons (g),
- SM gauge group is: $G_{sm} = SU(3)_c \times SU(2)_L \times U(1)_Y$,
- Since then the SM has been verified with great success $\rightarrow$ NC, charm, W,Z,top, CKM ... Higgs (2012),

➤The SM Lagrangian

- Free Lagrangian of (still massless) fermions:

$$\mathcal{L}_{0,\mathrm{ferm}} = \mathrm{i}\overline{\psi_f}\partial\!\!\!/\psi_f = \mathrm{i}\overline{\Psi^{\mathrm{L}}_L}\partial\!\!\!/\Psi^{\mathrm{L}}_L + \mathrm{i}\overline{\Psi^{\mathrm{L}}_Q}\partial\!\!\!/\Psi^{\mathrm{L}}_Q + \mathrm{i}\overline{\psi^{\mathrm{R}}_l}\partial\!\!\!/\psi^{\mathrm{R}}_l + \mathrm{i}\overline{\psi^{\mathrm{R}}_u}\partial\!\!\!/\psi^{\mathrm{R}}_u + \mathrm{i}\overline{\psi^{\mathrm{R}}_d}\partial\!\!\!/\psi^{\mathrm{R}}_d$$

- Minimal substitution:

$$\partial_\mu \rightsquigarrow D_\mu = \partial_\mu - \mathrm{i}g_2 T^a_{\mathrm{I}} W^a_\mu + \mathrm{i}g_1 \tfrac{1}{2} Y B_\mu = D^{\mathrm{L}}_\mu P_L + D^{\mathrm{R}}_\mu P_R$$

$$D^{\mathrm{L}}_\mu = \partial_\mu - \frac{\mathrm{i}g_2}{\sqrt{2}}\begin{pmatrix} 0 & W^+_\mu \\ W^-_\mu & 0 \end{pmatrix} - \frac{\mathrm{i}}{2}\begin{pmatrix} g_2 W^3_\mu - g_1 Y^{\mathrm{L}} B_\mu & 0 \\ 0 & -g_2 W^3_\mu - g_1 Y^{\mathrm{L}} B_\mu \end{pmatrix}$$

$$D^{\mathrm{R}}_\mu = \partial_\mu + \mathrm{i}g_1 \tfrac{1}{2} Y^{\mathrm{R}} B_\mu$$

- Photon identification:

"rotation":

$$\begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} = \begin{pmatrix} c_{\mathrm{W}} & s_{\mathrm{W}} \\ -s_{\mathrm{W}} & c_{\mathrm{W}} \end{pmatrix}\begin{pmatrix} W^3_\mu \\ B_\mu \end{pmatrix}$$

$$D^{\mathrm{L}}_\mu\Big|_{A_\mu} = -\frac{\mathrm{i}}{2} A_\mu \begin{pmatrix} g_2 s_{\mathrm{W}} - g_1 c_{\mathrm{W}} Y^{\mathrm{L}} & 0 \\ 0 & g_2 s_{\mathrm{W}} - g_1 c_{\mathrm{W}} Y^{\mathrm{L}} \end{pmatrix} \stackrel{!}{=} \mathrm{i}eA_\mu \begin{pmatrix} Q_1 & 0 \\ 0 & Q_2 \end{pmatrix}$$

where we used $Q = T^3_{\mathrm{I}} + \frac{Y}{2}$

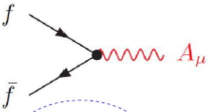
- **Fermion–gauge-boson interaction:**

$$\mathcal{L}_{\mathrm{ferm,YM}} = \frac{e}{\sqrt{2}s_{\mathrm{W}}} \overline{\Psi^{\mathrm{L}}_F} \begin{pmatrix} 0 & W\!\!\!/^{+} \\ W\!\!\!/^{-} & 0 \end{pmatrix} \Psi^{\mathrm{L}}_F + \frac{e}{2c_{\mathrm{W}}s_{\mathrm{W}}} \overline{\Psi^{\mathrm{L}}_F} \sigma^3 Z\!\!\!/ \Psi^{\mathrm{L}}_F$$

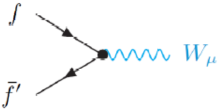
$$- e\frac{s_{\mathrm{W}}}{c_{\mathrm{W}}} Q_f \overline{\psi_f} Z\!\!\!/ \psi_f - eQ_f \overline{\psi_f} A\!\!\!/ \psi_f$$

(f=all fermions, F= all doublets)

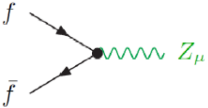
- **Feynman rules:**



$-\mathrm{i}Q_f e\gamma_\mu$ non-chiral



$\frac{\mathrm{i}e}{\sqrt{2}s_{\mathrm{W}}}\gamma_\mu P_L$ purely LH

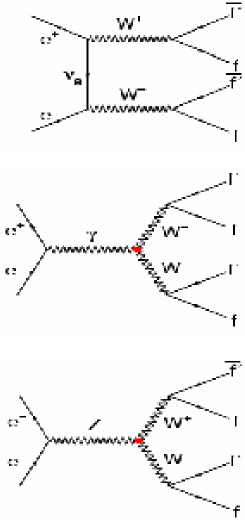


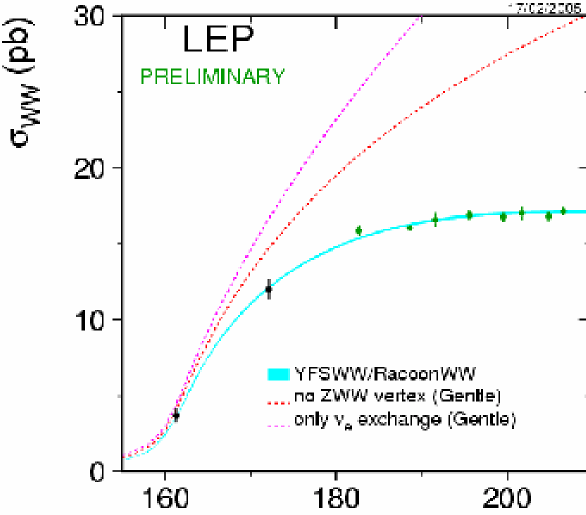
mixture LH-RH

$$\mathrm{i}e\gamma_\mu(g_f^L P_R + g_f^R P_L) = i\,\frac{g_2}{2\,c_W}\,(v_f - a_f\,\gamma_5)$$

with
$$\begin{cases} v_f = T_f^3 - 2\,Q\,s_W^2 \\ a_f = T_f^3 \end{cases}$$

The SM is great





W. Pauli → C.N. Yang: Where is the mass?

PHYSICAL REVIEW VOLUME 96, NUMBER 1 OCTOBER 1, 1954

Conservation of Isotopic Spin and Isotopic Gauge Invariance*

C. N. Yang † and R. L. Mills
Brookhaven National Laboratory, Upton, New York

(Received June 28, 1954)

It is pointed out that the usual principle of invariance under isotopic spin rotation is not consistant with the concept of localized fields. The possibility is explored of having invariance under local isotopic spin rotations. This leads to formulating a principle of isotopic gauge invariance and the existence of a **b** field which has the same relation to the isotopic spin that the electromagnetic field has to the electric charge. The **b** field satisfies nonlinear differential equations. The quanta of the **b** field are particles with spin unity, isotopic spin unity, and electric charge $\pm e$ or zero.

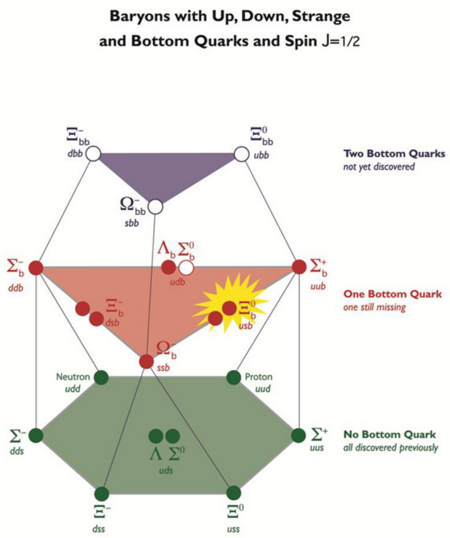
Fig. 1. Elementary vertices for **b** fields and nucleon fields. Dotted lines refer to **b** field, solid lines with arrow refer to nucleon field.

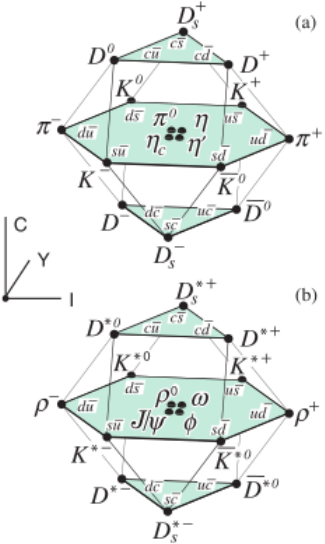
We next come to the question of the mass of the **b** quantum, to which we do not have a satisfactory answer. One may argue that without a nucleon field the Lagrangian would contain no quantity of the dimension of a mass, and that therefore the mass of the **b** quantum in such a case is zero. This argument is however subject to the criticism that, like all field theories, the **b** field is beset with divergences, and dimensional arguments are not satisfactory.

The origins: particle masses

- In the STANDARD MODEL, the MASS is an unwelcome property, as it destroys the SYMMETRIES,
- In fact, MASS arises thanks to the non-trivial properties of the physical VACCUM (= minimum of the energy),
- VACCUM makes the SYMMETRIES of the particles to look as if they were "HIDDEN".
- But, how did we arrive to this knowledge?

Bariones (3 quarks) y Mesones ($q\bar{q}$)





Hadron masses - chiral symmetry

- proton and neutron are formed by 3 quarks, p=(uud), n=(udd) ($M_p = 938$ MeV),
- Mesons are formed with 2 quarks, ex. pion=ud, ($m_\pi = 135$ Mev)
- But the mass of the pion is almost 1/10 of the proton mass! Should it not be 2/3 M_p ? Why is the pion so light? [In fact the ρ $(= q\bar{q})$ does fulfils this expectation, $M_\rho = 770$ MeV],
- The explanation of this observation comes from the phenomena of Spontaneous symmetry breaking (SSB),
- The Nucleon world is invariant under: $p \to n$ $(u \to d)$, i.e. a symmetria called ISOSPIN (Heisenberg),
- How is such symmetry realized in the hadronic world?

Nambu and Goldstone (1960)

Nobel Lecture: Spontaneous symmetry breaking in particle physics: A case of cross fertilization*

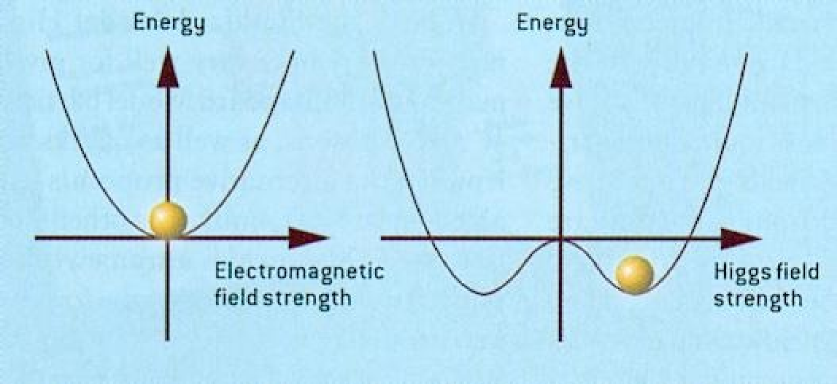
Yoichiro Nambu

Physical system	Broken symmetry
Ferromagnets	Rotational invariance (with respect to spin)
Crystals	Translational and rotational invariance (modulo discrete values)
Superconductors	Local gauge invariance (particle number)

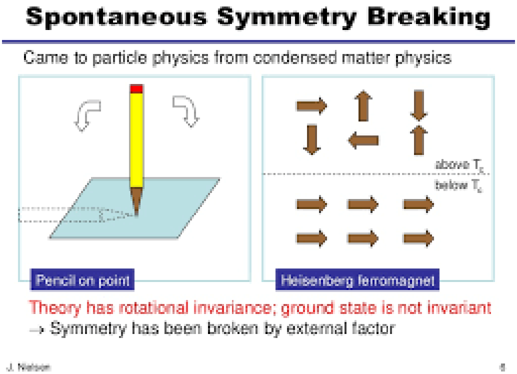
- Apply condensed matter ideas to particle physics
- ***Now the quantum vacuum is "the medium"***

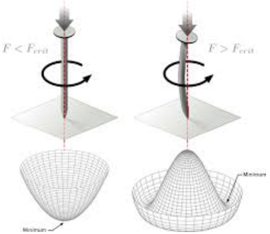
How could a symmetry be realized?

- A la Wigner-Weyl: the vaccum is invariant, e.g. QED,
- A la Nambu-Goldstone: the vaccum breaks the symmetry,



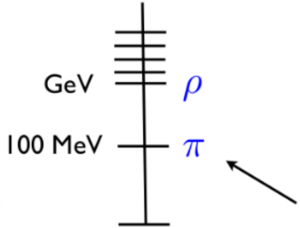
When a global symmetry is broken spontaneously → Massless Particles, ex. Piones!! (Goldstone Theorem, Nobel Prize to Nambu!)

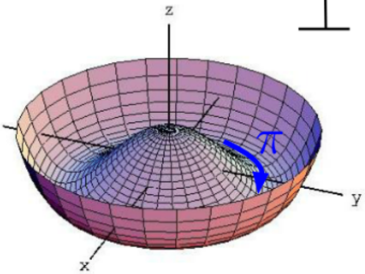

Spontaneous Symmetry Breaking
Came to particle physics from condensed matter physics
above T
below T
Pencil on point
Heisenberg ferromagnet
Theory has rotational invariance; ground state is not invariant
→ Symmetry has been broken by external factor
J. Nielsen
6


$F < F_{crit}$
$F > F_{crit}$

Inspired by QCD where one observes
that the (pseudo) scalars are the lightest states

Spectrum:





Are Pseudo-Goldstone bosons (PGB)

Mass protected by the global QCD symmetry!

$$\pi \rightarrow \pi + \alpha$$

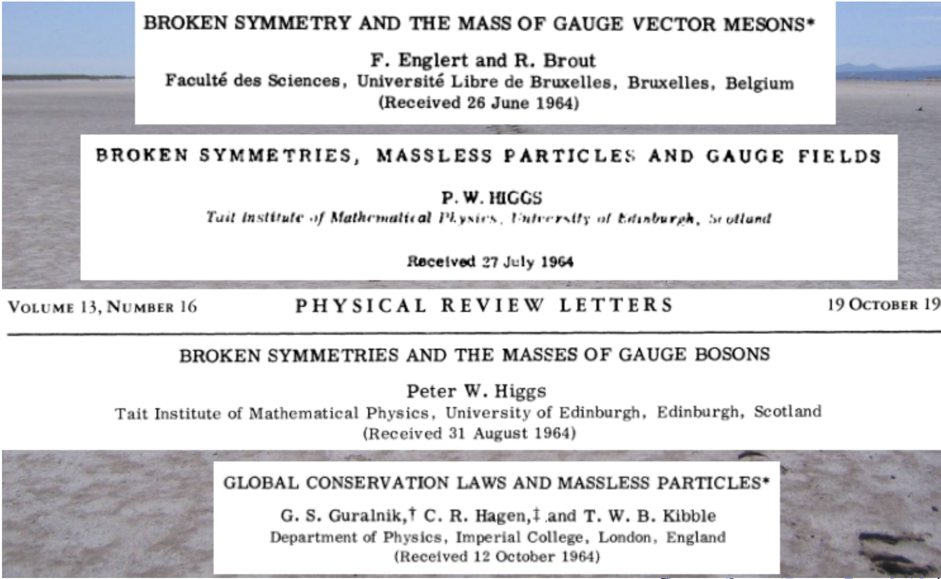
Brout-Englert-Higgs mechanism

In 1964, P. Higgs, Englert-Brou, found that it was possible to use Nambu-Goldstone ideas to generate Gauge boson mass,

- Englert-Brout udes diagramatic methos to prove that the uage boson propagator developed a pole in $p^2 \neq 0$, i.e. a mass was induced for gauge bosons,
- P. Higgs, followed a method based in the lagrangian (classical), to indetify an scalar remmant of this mechanism (Higgs Boson)

But BEH did not know exactly to which particles or forces this idea could be applied.

Why is titcalled the Higgs? (J. Ellis argument)



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)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

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

Received 27 July 1964

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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)

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)

From J. Ellis (Higgs Hunting, 2011)

- **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
- **Discussed in detail by Higgs in 1966 paper**

➤The Higgs sector: Spontaneous Symmetry Breaking

Complex scalar doublet: $\Phi(x) = \begin{pmatrix} \phi^+(x) \\ \phi^0(x) \end{pmatrix}$ $\quad Q = I_3 + \frac{Y}{2}$

four real d.o.f. !! $\quad Y = 1 \quad SU(2)_L \times U(1)_Y$

⬇ give mass

$W^+ W^- Z$

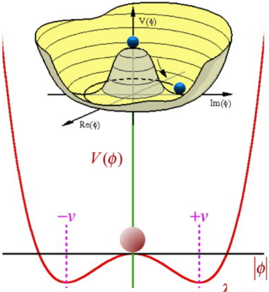
$$\mathcal{L}_H = (D_\mu \Phi)^+ (D^\mu \Phi) - V(\Phi)$$

Higgs potential: $V(\Phi) = -\mu^2 \Phi^+ \Phi + \frac{\lambda}{4} (\Phi^+ \Phi)^2$

Ground state: $< \Phi > = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$ with $v = \frac{2\mu}{\sqrt{\lambda}}$

Vacuum state !!

Brout-Englert-Higgs mechanism

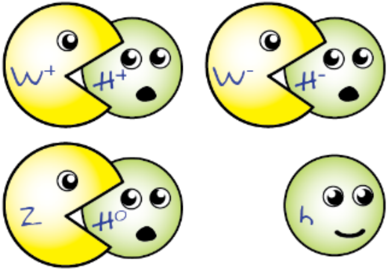


$$V(\phi) = \tfrac{1}{2}\mu^2\phi^\dagger\phi + \tfrac{1}{4}\lambda(\phi^\dagger\phi)^2$$

Groundstate at $|\phi_0| = \sqrt{\frac{-\mu^2}{\lambda}} \equiv \upsilon$

$$|\phi| = \sqrt{\phi^\dagger\phi} = \sqrt{\phi^{+\dagger}\phi^+ + \phi^{0\dagger}\phi^0}$$

$$V(\phi_0) = -\frac{\lambda}{4}\upsilon^4$$



The physical content becomes transparent by performing a transformation

$$\left.\begin{array}{l} W^{\pm}_{\mu} = \frac{1}{\sqrt{2}}(W^1_\mu \mp i W^2_\mu) \\ \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} W^3_\mu \\ B_\mu \end{pmatrix} \end{array}\right\}$$

mass eigenstates

where

$$\tan 2\theta_W = \frac{2 g_1 g_2}{g_2^2 - g_1^2} = \frac{2\frac{g_1}{g_2}}{1 - \frac{g_1^2}{g_2^2}} \quad \Rightarrow \quad \boxed{\tan\theta_W = \frac{g_1}{g_2}}$$

This diagonalizes the mass matrices *and gives* the physical masses:

$$M_W^2 W^+_\mu W^{-\mu} + \frac{1}{2}(A_\mu, Z_\mu) \begin{pmatrix} 0 & 0 \\ 0 & M_Z^2 \end{pmatrix} \begin{pmatrix} A^\mu \\ Z^\mu \end{pmatrix}$$

Yukawa interactions and fermion masses after SSB:

$$SU_L(2) \times U(1)_Y \to U_{em}(1).$$

$$\mathcal{L} = (D_\mu\phi)^*(D^\mu\phi) - y_d\bar{q}_L\phi d_R - y_u\bar{q}_L\phi^c u_R - g_l\bar{l}_L\phi e_R - \frac{\lambda}{2}\left(|\phi|^2 - v^2/2\right)^2$$

$$D^\mu = \partial^\mu + ig\frac{\vec{\tau}}{2} + ig'\frac{Y}{2}B^\mu, \qquad \phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}, \; \phi^c = i\sigma_2\phi^*$$

$$\phi^c = \frac{1}{\sqrt{2}}\begin{pmatrix} v + H(x) \\ 0 \end{pmatrix}$$

Goldstone bosons are "rotated away" by a gauge transformation (unitary gauge)

Notice that ϕ and ϕ^c are **both needed** to generate up and down fermion masses in the SM !!

$$m_e = y_e\frac{v}{\sqrt{2}}$$
$$m_u = y_u\frac{v}{\sqrt{2}}$$
$$m_d = y_d\frac{v}{\sqrt{2}}$$
$$\ldots$$

Fine, but too large hierarchy of Yukawa couplings in the SM:

$$y_e = \sqrt{2}\,\frac{m_e}{v} \simeq 3 \times 10^{-6}$$

$$y_t = \sqrt{2}\,\frac{m_t}{v} \simeq 1$$

Let alone the neutrino masses...

SM Yukawa lagrangian - 1 family

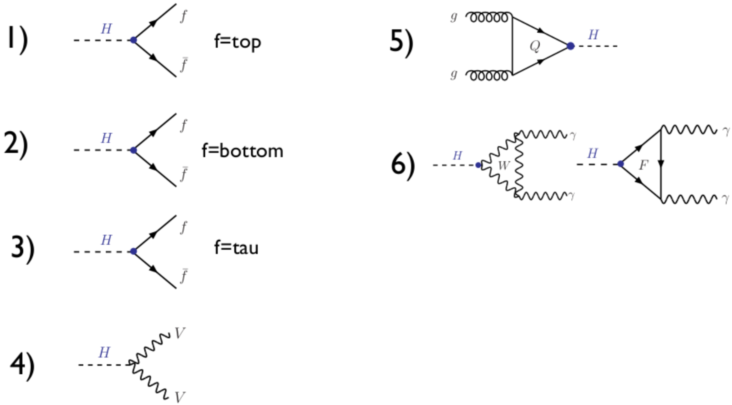
$$\mathcal{L}_Y = y_d \bar{Q}_L \Phi d_R + y_u \bar{Q}_L \Phi u_R + h.c. \tag{7}$$

- $\bar{Q}_L = (\bar{u}_L, \bar{d}_L)$, $\quad \Phi = (\phi^+, \phi^0)^T$,
- After SSB: $\quad \phi^0 = \frac{1}{\sqrt{2}}(v + h + iG_z)$
- $\bar{Q}_L \Phi = (\bar{u}_L, \bar{d}_L)(\phi^+, \phi^0)^T = \bar{u}_L \phi^+ + \bar{d}_L \phi^0$
- $\bar{Q}_L \Phi d_R = \bar{u}_L d_R \phi^+ + \bar{d}_L d_R \phi^0$
- $y_d \bar{Q}_L \Phi d_R = (\bar{d}_L d_R) y_d \frac{1}{\sqrt{2}}(v + h + iG_z) + ...$

$$\mathcal{L}_Y = \frac{1}{\sqrt{2}}(y_d v + y_d h)\bar{d}_L d_R + ... = \frac{1}{\sqrt{2}} y_d v \bar{d}_L d_R + \frac{1}{\sqrt{2}} y_d h \bar{d}_L d_R + ... \tag{8}$$

$\rightarrow m_d = \frac{1}{\sqrt{2}} y_d v \quad$ and $\quad (hdd) = \frac{m_d}{v}$

Higgs couplings:

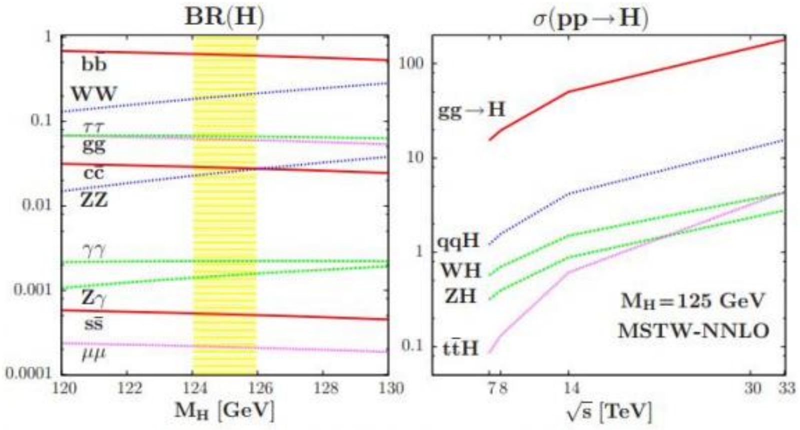


- $(hVV): \quad \frac{2m_V^2}{v}, \qquad (hff): \quad \frac{m_f}{v}$
- $(hhh): \quad \frac{3}{2}\lambda v, \qquad (hhhh): \quad \frac{3}{2}\lambda$

Summary of Higgs properties

- SSB is used to generate masses in the SM,
- Minimal Higgs sector involves one Higgs doublet: $\Phi = [G^{+}, \frac{1}{2}(v + h + iG_z)]$, and this is enough to generate gauge bosons and fermion masses,
- Higgs mass is a free parameter within the SM,
- Higgs couples to other particles with a strength proportional to the particle mass,
- To produce the Higgs we need high energy collsions able to produce heaviest particles of the SM

3. SM Higgs properties and its detection at LHC



4 de Julio en el LHC

4. Higgs mass and quadratic divergences

5. The Higgs and the roots of Physics