Six lectures on the Standard Theory of Elementary Particle Physics

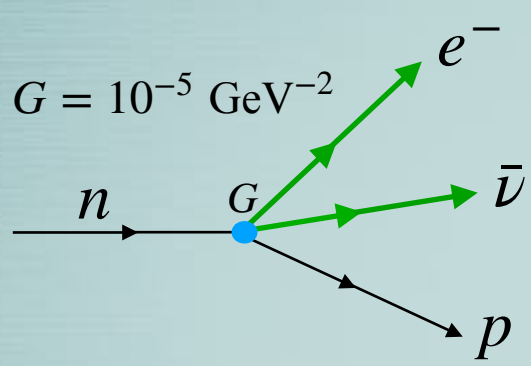
Luciano Maiani,
Beijing University
Universitá di Roma Sapienza
Beijing, 14 October2026



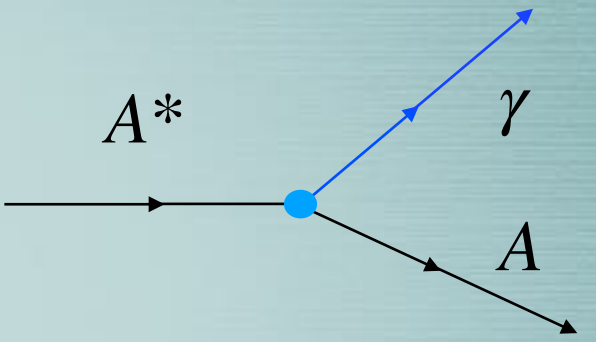
Lecture 2
Breaking the Symmetry

Fermi Theory of the Weak Interactions

• In 1933, after the discovery of the neutron as a component of the atomic nuclei and following the neutrino hypothesis by W. Pauli, E. Fermi proposed a theory of β-radioactivity as due to the neutron-proton transition:



The neutron emits the $e^-\bar{\nu}$ pair, in analogy with the electromagnetic de-excitation of an atom:



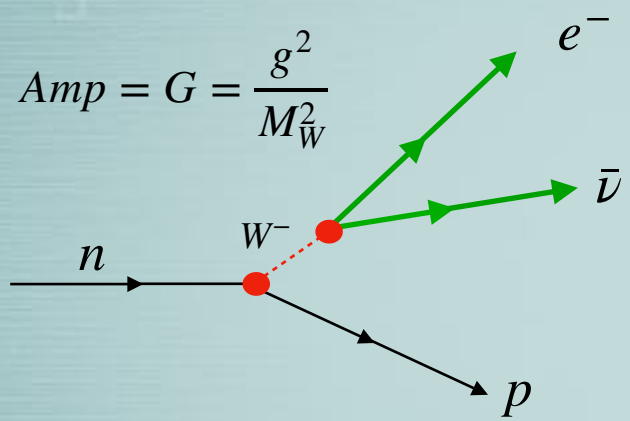
- The process is regulated by a very small coupling, the Fermi constant G
- Accordingly, neutrino has a very ***weak interaction*** with matter

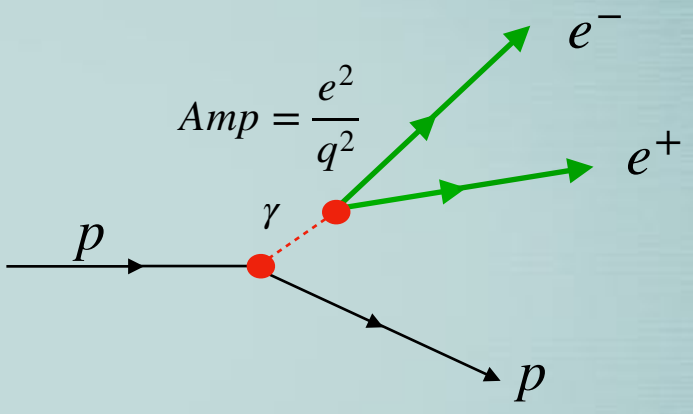
However, if you have a very intense flux of neutrinos, as in a nuclear reactor, you may observe events of the inverse beta decay process: $\bar{\nu} + p \rightarrow e^+ + n$ (Reines and Cowan,1953).

The neutrino is a real particle, not a ghost!!

Towards a Unified Theory of Electromagnetic and Weak Interaction

- Fermi made his theory *in analogy* to electromagnetism.
- The first step toward *a real* unification was the hypothesis that Weak Interactions are transmitted by a new particle called *the Intermediate Vector Boson.*
- To reproduce Fermi theory IVB has to have a very large mass





- In 1961, on the basis of the V-A structure of the observed weak interactions, Sheldon Glashow proposed a Unified Theory ***with 4 intermediaries***: W^+, W^-, Z^0, γ.

- ***The theory was able to describe W&E.m. interactions of electrons and muons only***;
- the theory predicted new fenomena, like the existence of neutrino reactions in which a neutrino appears in the final state:

$$\nu + N \rightarrow \nu + N' \ (\textbf{\textit{neutral current processes}})$$

instead of transforming into a charged lepton, as it happens in the inverse beta decay:

$$\nu + n \rightarrow e^- + p \ \ (\textbf{\textit{charged current processes}}).$$

Unified Theory of Electromagnetic and Weak Interaction: only electrons and neutrinos

The 1961 Glashow theory left 3 questions open. ***The answers led to the present Unified Standard Theory*** (these remarks: Glashow 2023)

1. Can we give a mass to the IVB leaving the photon massless? (solution: Weinberg & Salam, 1967, using the Higgs -Brout-Englert mechanism);
2. Can we extend the interaction to the hadrons, i.e with a coupling of the neutral IVB (Z^0) in agreement with the observed strong suppression of $K \to \mu^+\mu^-$? (solution: Glashow, Iliopoulos, Maiani: GIM mechanism, 1970, charmed particles predicted);
3. Can we obtain a consistent renormalizable quantum theory like QED? (proved by: 't-Hooft & Veltman, 1972).

1. A Yang-Mills theory of Electromagnetic and Weak Interactions

S. L. Glashow, *Partial Symmetries of Weak Interactions*, Nucl. Phys. **22** (1961) 579.

- The success of the V-A theory has given momentum to the idea that Fermi interactions are mediated by an intermediate vector boson, IVB;
- Yang - Mills theory provides the conceptual framework to link the IVB to the symmetries which are associated to the weak currents;
- First proposals by J. Schwinger (in the '50s): he considered O(3), with gauge fields $W^{\pm}$ and A;
- S. L. Glashow (1961) extended O(3) to SU(2) ⊗U(1) and produced the first unified electroweak theory (for leptons only!).

- Matter: $\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$; e_R ↑ T^+ ↓ T^-

$$\nu_{L,R} = \frac{1 \mp \gamma_5}{2}\nu, \text{ same for } e$$

$SU(2)_{Weak}$: $[T^+, T^-]=2T^3$

Y=Weak Hypercharge: $Q= T^3 +1/2\ Y$

Y= -1, -2

- Y commutes with $SU(2)_{Weak}$
- Y is necessary to keep Q in the gauge group

→ G= $SU(2)_{Weak}$⊗$U(1)_Y$

Gauge Fields: $W^{1,2,3}_{\mu}$, B_{μ}

V-A

- Lepton fields appear in the Fermi interaction always multiplied by $(1-\gamma_5)$
- We introduce fields with definite chirality, e_L, ν_L
- e_L: destroys a ***left-handed electron*** and creates a ***right-handed positron***
- e_R: destroys a ***right-handed electron*** and creates a ***left-handed positron***
- Similarly for ν_L.
- If neutrino has zero mass, we can stop with ν_L: this is the two-component neutrino theory (Landau, Lee&Yang…)
- The electron is a Dirac field: we must introduce e_R, which does not appear in the Fermi interaction, thus is an $SU(2)_{Weak}$ singlet.
- $Q(e_R) = -1 = Y(e_R)/2 \rightarrow Y(e_R) = -2$
- Same considerations for the ν_μ–μ doublet

Matter $\begin{pmatrix}\nu_L \\ e_L\end{pmatrix}_{Y=-1/2}$; $(e_R)_{Y=-2}$; $\begin{pmatrix}\nu_{\mu L} \\ \mu_L\end{pmatrix}_{Y=-1/2}$; $(\mu_R)_{Y=-2}$

Gauge Fields (forces): $W_\mu^{1,2,3}; B_\mu$

$$L_{mass} = m_e\,\bar{e}e = m_e(\bar{e}_R\,e_L + h.c.) \;:\Delta I_W = 1/2$$

The (Dirac) electron mass couples e_L with e_R, so it is not invariant:

All particles are massless in the symmetry limit!

All particles are massless in the symmetry limit ??????

S. L. Glashow, *Partial Symmetries of Weak Interactions*, Nucl. Phys. **22** (1961) 579.

- We recently introduced the notion of "partial-symmetry" -- invariance of only part of the Lagrange function under a group of infinitesimal transformations 4).
- The part of the Lagrange function bilinear in the field variables which produces masses of the elementary particles need not be invariant under a partial-symmetry. Corresponding "partial-conservation laws" become conservation laws only with the neglect of appropriate masses or mass differences. This is the only sort of symmetry which could relate the massive decay intermediaries to the massless photon. (1961)

In the Weinberg-Salam theory (1967), masses are generated by the
spontaneous symmetry breaking of the gauge symmetry
(the Brout-Englert-Higgs mechanism)

2. Spontaneous symmetry breaking

P. W. Higgs, Phys. Rev. **145** (1966) 1156.
F. Englert, R. Brout, Phys. Rev. Lett. **13** (1964) 321.:
see: L. Maiani, "Electroweak Interactions,"
CRC Press, 2015, ISBN 978-0-429-15980-0

Abelian case

- ***Global Symmetry U(1)***:
- Introduce scalar, complex field, 2 real components:

$$\phi(x) = \frac{1}{\sqrt{2}}[\phi_1(x) + i\phi_2(x)];\ \ \phi(x) \to e^{i\alpha}\phi(\mathrm{x})$$

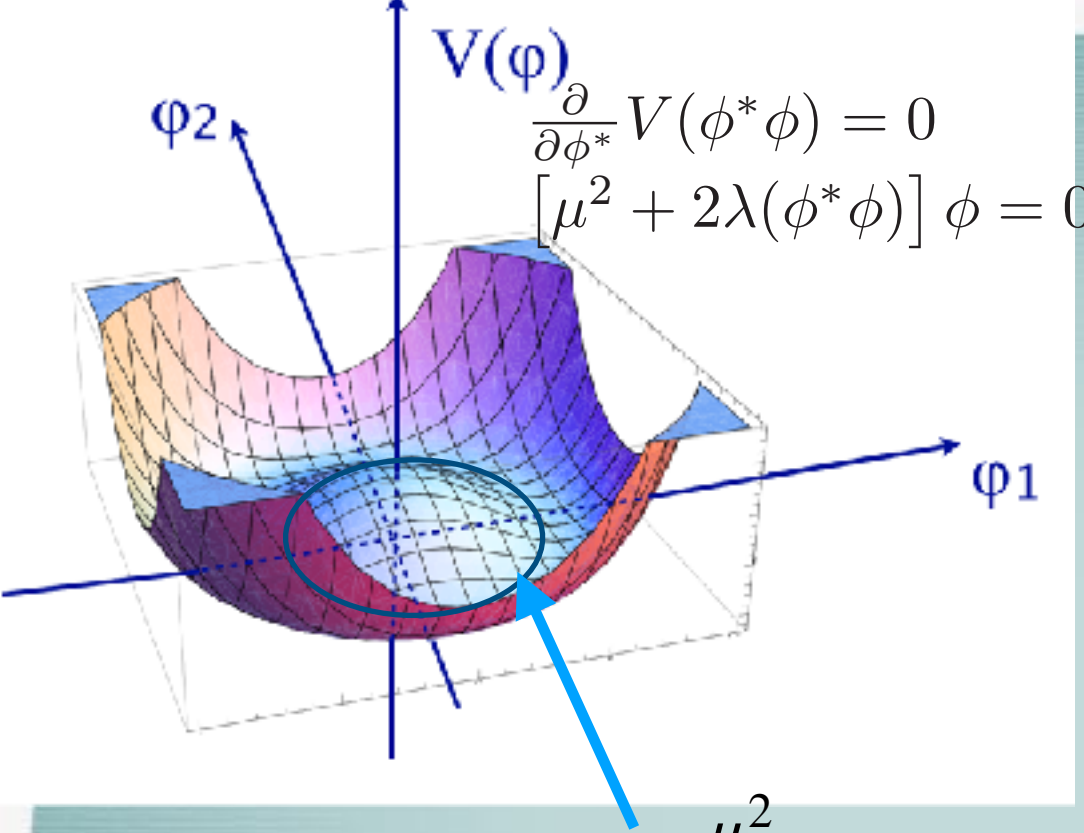
- and a lagrangian invariant under ***global*** phase transformations

$$\mathcal{L} = \partial_\mu \phi^* \partial^\mu \phi - V(\phi) \qquad V(\phi) = C + \mu^2 \phi^* \phi + \lambda(\phi^* \phi)^2$$

- This invariant Lagrangian is renormalizable by power counting (can you prove it?)
- Stability: $\lambda > 0$
- Ground state (vacuum): minimum of H:

$$\mathbf{H} = \int d^3x\ H(x);\ \ H(x) = \vec{\nabla}\phi^\star \cdot \vec{\nabla}\phi + V(\phi)$$

- Translationally invariant vacuum: ϕ=const.
- therefore ϕ must be the minimum of V.
- The minimum may not be invariant under the symmetry: ***spontaneous symmetry breaking***



$$\frac{\partial}{\partial\phi^*}V(\phi^*\phi)=0$$

$$\left[\mu^2+2\lambda(\phi^*\phi)\right]\phi=0$$

$$V(\phi)=C+\mu^2\phi^*\phi+\lambda(\phi^*\phi)^2$$

$\lambda > 0$, solutions depend upon the sign of μ^2

(a) $\mu^2 > 0$:

$\varphi = 0$

Exact symmetry, degenerate masses for $\varphi_{1,2}$ (or $\varphi^{+/-}$)

(b) $\mu^2 < 0; \quad \phi^*\phi = \dfrac{-\mu^2}{2\lambda}$

$$\eta=\sqrt{\phi^*\phi}=\sqrt{\frac{-\mu^2}{2\lambda}}$$

$$V(0)=C$$

$$V(\phi^*\phi)|_{min.}=C-\frac{\mu^4}{4\lambda}<C$$

Broken symmetry: the stable vacuum corresponds to $\varphi \neq 0$.

What is the spectrum? Develop fields around η

Note. Minima on the circle: $\varphi=\eta e^{i\alpha}$ There are infinitely many degenerate vacua, differing by a phase transformation

A more convenient notation

$$V = \lambda(\phi^*\phi - \eta^2)^2$$

- Minimum in $\phi=\eta$;
- Coeff. of quadratic term around $\phi=0$ is negative: $V^{(2)} = -2\lambda\eta^2\phi^*\phi$
- Oscillations around stable minimum parameterized by σ and ξ:

$$\phi(x) = \eta + \frac{\sigma + i\xi}{\sqrt{2}}$$
$$\phi^*\phi - \eta^2 = \sqrt{2}\eta\sigma + \sigma^2 + \xi^2$$

- Expanding the Lagrangian in powers of the fields we find:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma + \partial_\mu\xi\partial^\mu\xi) - \frac{1}{2}(4\lambda\eta^2)\sigma^2 + interactions$$

- "interactions" are terms at least cubic in the fields σ and ξ
  - no term linear in the fields: we expanded around a minimum
  - σ is a massive scalare field: $m_\sigma^2=4\lambda\eta^2$
- no term quadratic in ξ: the field ξ is a massless (Nambu-Goldstone) boson
- ξ appears in the kinetic and interaction terms: it is a real physical particle

The existence of a massless scalar particle is the sign of the spontaneous breaking of a continuous global symmetry (Y. Nambu1961, J. Goldstone 1962).

3.The Higgs-Brout-Englert miracle

U(1) gauge theory

$$D_\mu\phi = [\partial_\mu - igA_\mu]\phi$$

$$L_{\phi W} = \left(D_\mu\phi\right)^\dagger \left(D^\mu\phi\right) - V(\phi)\,;\;\; V(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

$$\phi(x) = \eta + \frac{\rho(x) + i\xi(x)}{\sqrt{2}} + \ldots = \eta(1 + \frac{\rho(x)}{\eta\sqrt{2}})(1 + \frac{i\xi(x)}{\eta\sqrt{2}}) + quadratic + \ldots =$$

$$= e^{i\frac{\xi(x)}{\eta\sqrt{2}}}\ (\eta + \frac{\rho(x)}{\sqrt{2}}) + \ldots = \ U[\xi(x)](\eta + \frac{\rho(x)}{\sqrt{2}}) + \ldots$$

- with a gauge transformation ***we can make φ real and completely independent from ξ*** (dots represent "interaction terms"):

- In the ***Unitary Gauge***, the Goldstone boson disappears and the scalar spectrum consists only of a scalar massive particle (the field ρ): the ***Higgs-Brout-Englert boson***.

- the gauge invariant scalar lagrangian, in the unitary gauge ϕ =real, is:

$$L = \frac{1}{2}\partial_\mu\rho\partial^\mu\rho + g^2\eta^2 A_\mu A^\mu(1 + \frac{\rho}{\eta\sqrt{2}})^2 - V = \ \frac{1}{2}[\partial_\mu\rho\partial^\mu\rho + m_\rho^2) + 2g^2\eta^2 A_\mu A^\mu + \text{interactions}$$

The Higgs-Brout-Englert miracle (cont'd)

$$\mathcal{L}_{loc.symm} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} =$$

$$= \frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma + m_\sigma^2\sigma^2) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(2g^2\eta^2)A_\mu A^\mu + interactions$$

- the particle spectrum of the ***unbroken theory*** had two massive scalars and one massless vector
- ***spontaneous broken global symmetry***: one massles scalar (Goldstone boson), one massive scalar, one massles vector
- Higgs-Brout-Englert mechanism: the ***spontaneously broken local symmetry*** has no massless particles! spectrum made by one massive scalar and one massive vector

—	–	ϕ_1	ϕ_2	A^μ	no. degrees of freedom
glob.&loc. sym.	$\mu^2 > 0$	μ	μ	0	1+1+2=4
global sym.	$\mu^2 < 0$	M_H	0	0	1+1+2=4
local sym.	$\mu^2 < 0$	M_H	—	M_A	1+0+3=4

Table 1: Mass spectrum of the particles in the Abelian model.

The Goldstone boson provides the missing state of helicity = 0 to make a massive vector particle!

4. The Weinberg-Salam theory (leptons only)

S.~Weinberg, *A Model of Leptons*, Phys. Rev. Lett. **19** (1967) 1264.
A. Salam, in N. Svartholm: *Elementary Particle Theory*, Proc. Nobel Symp., Lerum Sweden (1968) 367.

- We adopt the non-abelian symmetry $SU(2)_W \otimes U(1)_Y$ introduced by Glashow, as done by S. Weinberg and A. Salam in 1967-68
- Assume scalar, complex fields, making a doublet with Y=+1 and a lagrangian invariant under global $SU(2)_W \otimes U(1)_Y$ transformations:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \qquad \mathcal{L} = \partial_\mu \phi^\dagger \partial^\mu \phi - V(\phi)$$

$$V(\phi) = C + \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

$$\mathbf{H} = \int d^3x \; H(x); \quad H(x) = \vec{\nabla}\phi^+ \cdot \vec{\nabla}\phi + V(\phi)$$

- Minimum of H in $\phi=\eta$: $\phi(x) = \bar{\phi} + \xi(x); \; \bar{\phi} = \begin{pmatrix} 0 \\ \eta \end{pmatrix}$
- Oscillations above vacuum parameterized by ξ: $\xi = \phi - \bar{\phi} = \begin{pmatrix} \frac{\xi_1 + i\xi_2}{\sqrt{2}} \\ \\ \frac{\sigma + i\xi_4}{\sqrt{2}} \end{pmatrix}$
- Expanding the Lagrangian:
- $$\mathscr{L} = \frac{1}{2}(\partial_\mu \xi_i \partial^\mu \xi_i) + \frac{1}{2}(\partial_\mu \sigma \partial^\mu \sigma) - \frac{1}{2}(4\lambda^2)\sigma^2 + interactions$$
- "interactions" are terms of order 3 or higher in the fields;
- σ is a massive scalar field: $m_\sigma^2 = 4\lambda\eta^2$
- the fields ξ^i are the Goldstone bosons, as indicated by the lack of $(\xi_i)^2$ term in $\mathcal{L}$; there is one Goldstone boson for each broken generator.

Goldstone fields are eliminated by a local gauge transformation

- Given an SU(2) spinor, ϕ, there exists a SU(2)xU(1) transformation that brings it in a standard form, with only the down component $\neq 0$ and real (prove it)
- Write the non vanishing component as $\eta+\sigma/\sqrt{2}$; then:

$$\phi = U \begin{pmatrix} 0 \\ \eta + \frac{\sigma}{\sqrt{2}} \end{pmatrix}; \quad U = e^{i\epsilon^A T^A} e^{i\epsilon Q}$$

where T^A, A=1, 2, 3 are the three broken generators and Q the conserved electric charge.

- The generic spinor is the gauge-transformed of a "standard" diagonal spinor, with only one real component, φ_{diag}. Unitary gauge: $\varphi = \varphi_{diag}$; $\varphi_{diag}(\eta) = \phi_0$

$$L = (D_\mu(A)\phi_0)^+ D_\mu(A)\phi_0 - V(\phi_0) = \frac{1}{2}\,\partial_\mu\sigma\partial^\mu\sigma - V + \frac{1}{2}\,\mu^2_{AB}(\phi_0)\; A^A_\mu A^{\mu B} + \ldots;$$

$$\mu^2_{AB} = g_A g_B\; (\phi_0^\dagger\{T^A, T^B\}\phi_0)$$

- ***The same miracle***. Adding the Yang Mills lagrangian, one sees that the last term gives a mass to all the gauge fields whose generators do not annihilate the vacuum state: $W^\pm$, Z(Higgs-Brout-Englert mechanism).
- Photon remains massless.
- The 3 would-be Goldstone bosons of the broken global symmetry provide the longitudinal spin states of W and Z.

Masses of the gauge bosons in SU(2)xU(1)

- in our case: $g^A T^A A^A_\mu = g\frac{\tau^i}{2} W^i_\mu + \frac{1}{2} g' B_\mu$
- in the basis of the fields W^1, W^2, W^3, B, one obtains:

$$(\mu^2)_{ab} = M_W^2 \delta_{ab},\ a,b = 1,2;\ M_W^2 = \frac{1}{2} g^2 \eta^2$$

$$\mu^2 = M_W^2 \begin{pmatrix} g^2 & -gg' \\ -gg' & g'^2 \end{pmatrix}$$

- the W^3, B matrix has Det(μ^2)=0, corresponding to the massless photon.
- Defining the pysical Z and photon field as

$$Z_\mu = cos\theta\ W^3_\mu\ -\ sin\theta\ B_\mu;\ A_\mu = sin\theta\ W^3_\mu\ +\ cos\theta\ B_\mu$$

one finds:

$$\tan\theta = \frac{g'}{g}$$

and

$$M_W^2 = \frac{g^2}{2}\eta^2;\ M_Z^2 = \frac{M_W^2}{cos^2\theta};\ M_A^2 = 0$$

Currents and Fermi couplings

- Back to the leptons: $D_\mu(A)\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L = [\partial_\mu + i(g\frac{\tau^i}{2}W^i_\mu - \frac{1}{2}g'\,B_\mu)]\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L$

$$D_\mu(A)\,e_R = [\partial_\mu + i(-g'B_\mu)]e_R$$

- from this, one finds easily the interaction lagrangian:

$$L_{int} = \frac{g}{2\sqrt{2}}[W^\lambda\, J^{weak}_\lambda + h.c.] + \frac{g}{cos\theta}Z^\lambda(J^3_\lambda - sin^2\theta J^{e.m.}_\lambda) + eJ^{e.m.}_\lambda A^\lambda$$

$$J^{weak}_\lambda = \bar{\nu}_e\gamma_\lambda(1-\gamma_5)e + (e\to\mu);$$

$$J^3_\lambda = \frac{1}{4}[\bar{\nu}_e\gamma_\lambda(1-\gamma_5)\nu_e - \bar{e}\gamma_\lambda(1-\gamma_5)e + (e\to\mu)];$$

$$J^{e.m.}_\lambda = -\bar{e}\gamma_\lambda e - \bar{\mu}\gamma_\lambda\mu$$

- and the leptonic charged current and neutral current Fermi interactions between e.g. electronic and muonic leptons:

$$L_{Fermi} = \frac{G}{\sqrt{2}}[\bar{\nu}_\mu\gamma_\lambda(1-\gamma_5)\mu + ...][\bar{e}\gamma^\lambda(1-\gamma_5)\nu_e + ...] +$$
$$+\frac{G}{\sqrt{2}}[\bar{\nu}_\mu\gamma_\lambda(1-\gamma_5)\nu_\mu + ...][\bar{e}\gamma_\lambda(g_V - g_A\gamma_5)e + ...]$$

$$\frac{G}{\sqrt{2}} = \frac{g^2}{8M_W^2} \qquad g_V = -\frac{1}{2} + 2\sin^2\theta;\ g_A = -\frac{1}{2} \qquad \text{Expt}: \ sin^2\theta_Z = 0.23122$$

Note: relative normalization of neutral and charged currents is fixed

5. The electron mass

- The Higgs doublet has: I_W=1/2, Y= -1 and it can couple the left-handed electron doublet, e_L (I_W=1/2, Y= -1) to the singlet e_R (I_W=1/2, Y= -2):

$$\ell_L = \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}; \quad \phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

- Trilinear (Yukawa) coupling:

$$\mathscr{L}_e = g_e(\bar{e}_R \phi^- \nu_{eL} + \bar{e}_R \bar{\phi}^0 e_L + h.c.)$$

- In the vacuum configuration:

$$(< \phi^{\pm} >_0 = 0, < \phi^0 >_0 = \eta :$$

$$\mathscr{L}_e \rightarrow g_e \eta(\bar{e}_R e_L + \bar{e}_R e_L) = g_e \eta(\bar{e}e) \;\rightarrow\; m_e = g_e \eta$$

and: $M_W = \dfrac{g}{\sqrt{2}}\eta; \; M_Z = \dfrac{g}{\cos\theta_W \sqrt{2}}\eta$

The Higgs boson mass

- The physical scalar field, σ, is the ***Higgs boson***;
- Its coupling to the vector bosons is fixed by their masses and by the value of η:

$$L_{\sigma VV} = \left[2\frac{\sigma}{\sqrt{2}\eta} + (\frac{\sigma}{\sqrt{2}\eta})^2\right](M_W^2 W_\mu^\dagger W^\mu + \frac{1}{2}M_Z^2 Z_\mu Z^\mu)$$

- We know η:

$$\frac{G}{\sqrt{2}} = \frac{g^2}{8M_W{}^2} = \frac{g^2}{8(g^2\eta^2/2)} = \frac{1}{4\eta^2} \quad \eta = (\frac{1}{2\sqrt{2}G})^{1/2} \approx (\frac{10^5\,\mathrm{GeV}^2}{1.16\cdot 2.82})^{1/2} \approx 170\mathrm{GeV}$$

$$m_H^2 = 4\lambda\eta^2$$
$$m_H = \sqrt{\lambda}\ 340\ \mathrm{GeV}$$

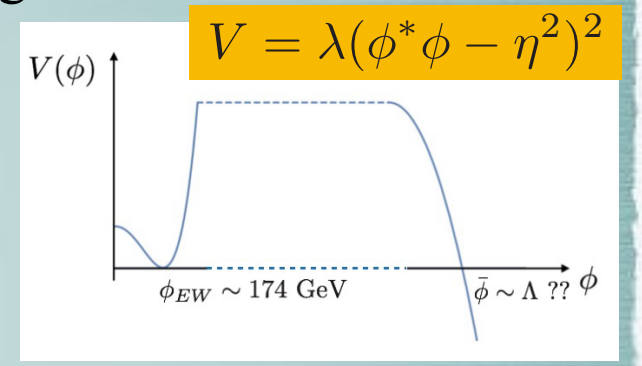
- The direct ratio between σ-VV coupling and the V mass, f mass, σ-VV, $\sigma - f\bar{f}$ and σ-σ-VV are the signatures of the Higgs mechanism.

The Higgs boson mass ($M_H = \eta\lambda$) depends from λ and it ***cannot be predicted from Weak Interaction data***.

6. Bounds to the Higgs boson mass

$$\beta(\lambda) = \frac{1}{16\pi^2}\left(4\lambda^2 - 36\, g_t^4 + 12\, g_t^2\right) \;+\; \text{smaller EW corr.s}$$

- For a given λ, g_t can drive it to smaller values until λ becomes negative at some energy scale $q \sim \Lambda_{low}$
- potential decreasing at value of the field $\varphi \sim \Lambda_{low}$ making the electroweak minimum φ_{EW} to become unstable!
- alternatively, λ too large can generate a Landau pole at some energy scale Λ_{up}
- the initial value of λ, say at $q \sim M_W$, must be between an upper and a lower bound if we want to avoid all that until we reach an energy scale, Λ, where new interactions may come in, that may correct the "bad" behavior of $\lambda(t)$. Possible choices are $\Lambda = M_{GUT} \sim 10^{14}$ GeV or $\Lambda = M_{Planck} \sim 10^{19}$ GeV.

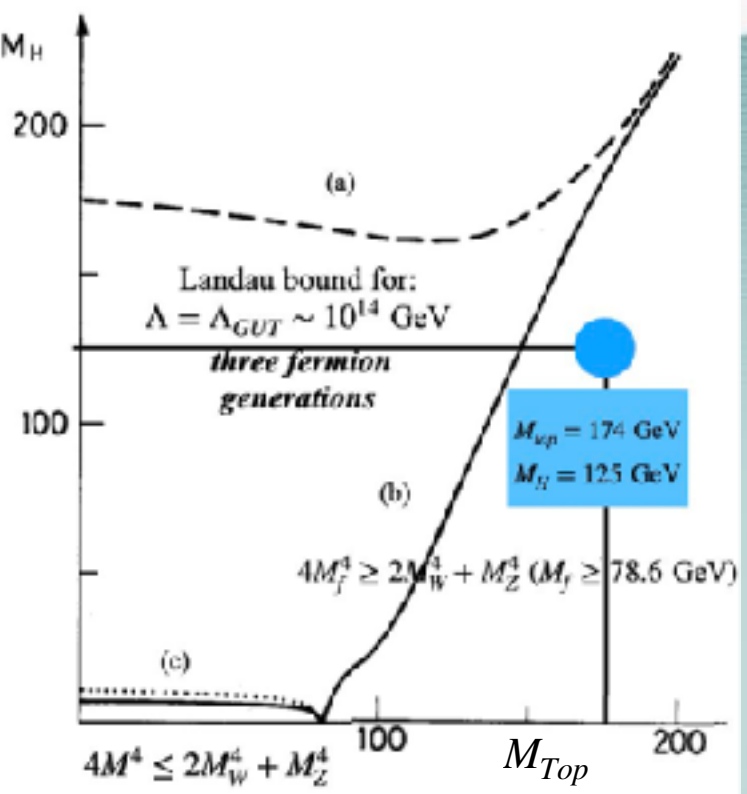


- Bounds have been derived for $\Lambda = M_{GUT}$, to leading log approximation by Cabibbo et al.

N. Cabibbo, L. Maiani, G. Parisi and R. Petronzio, Nucl. Phys. **B158** (1979) 295

- higher order estimates are found in:

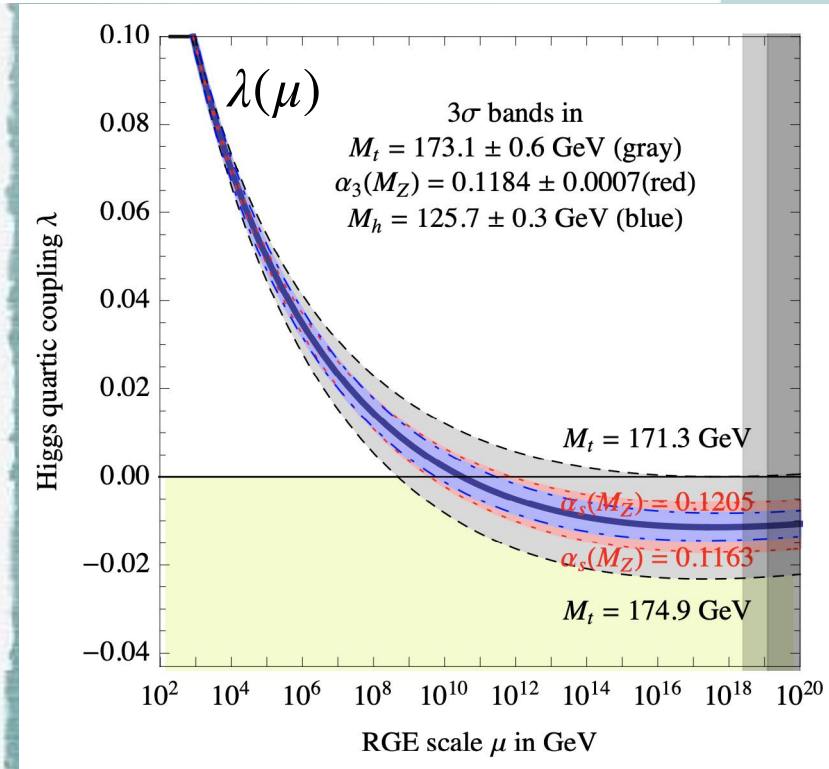
G. Altarelli and G. Isidori, Phys. Lett. **B 337** (1994) 141;
M. Sher, Phys. Lett. **B 317** (1993) 159, **B 331** (1994) 448.
G. Degrassi *et al.* , JHEP **1208**} (2012) 098



LL approximation

N. Cabibbo, L. Maiani, G. Parisi and R. Petronzio, Nucl. Phys. **B158** (1979) 295

$$150 \text{ GeV} < M_H < 180 \text{ GeV} ,$$
$$(\Lambda = 10^{15} \text{ GeV} , \ m_t = 174 \text{ GeV})$$



NLL approximation

G. Altarelli and G. Isidori, Phys. Lett. **B 337** (1994) 141;
M. Sher, Phys. Lett. **B 317** (1993) 159, **B 331** (1994) 448;
G. Degrassi *et al.* , JHEP **1208**} (2012) 098