

Six lectures on the Standard Theory of Elementary Particle Physics

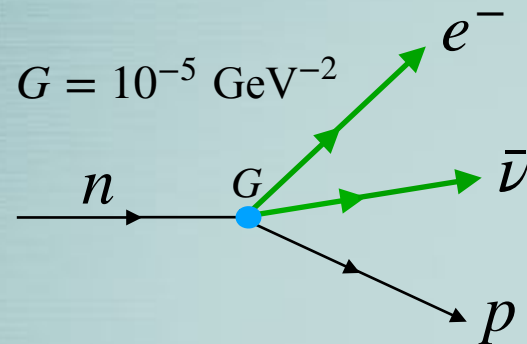
*Luciano Maiani,
Beijing Univerity
Università di Roma Sapienza
Beijing, 14 October 2026*



Lecture 2
Breaking the Symmetry

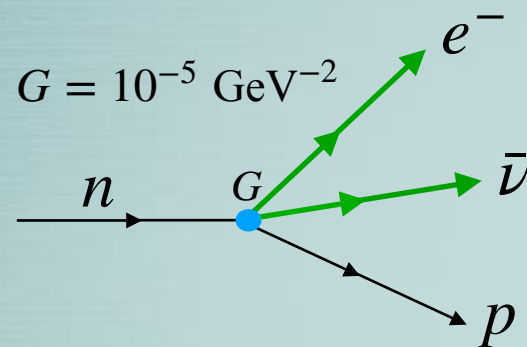
Fermi Theory of the Weak Interactions

- 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 decay:

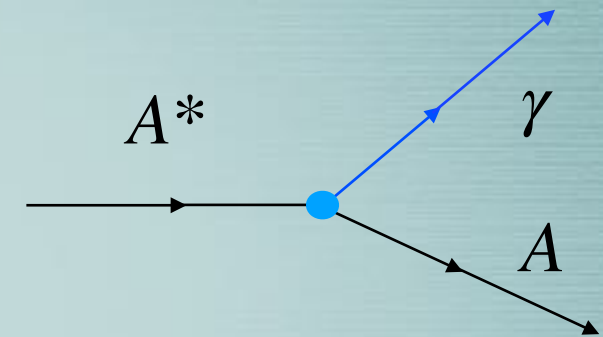


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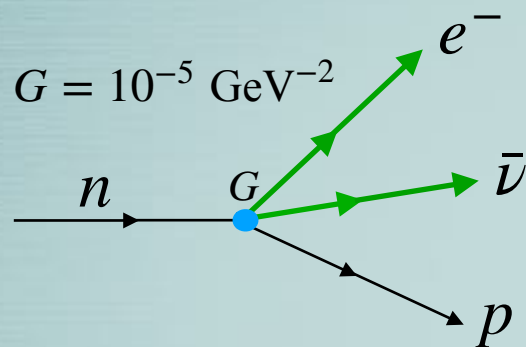


The neutron emits the $e^-\bar{\nu}$ pair, in analogy with the electromagnetic de-excitation of an atom:

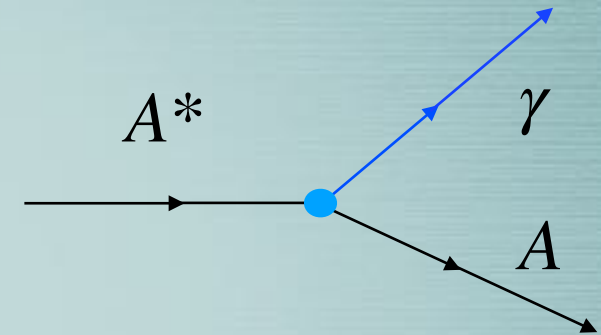


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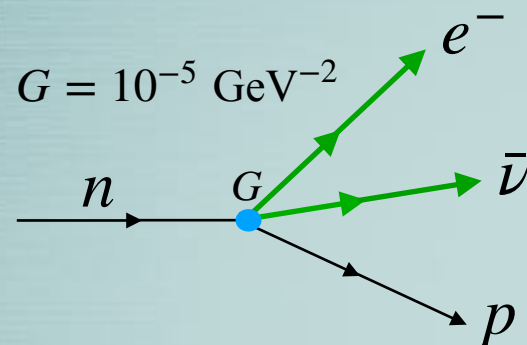


- The process is regulated by a very small coupling, the Fermi constant G
- Accordingly, neutrino has a very ***weak interaction*** with matter

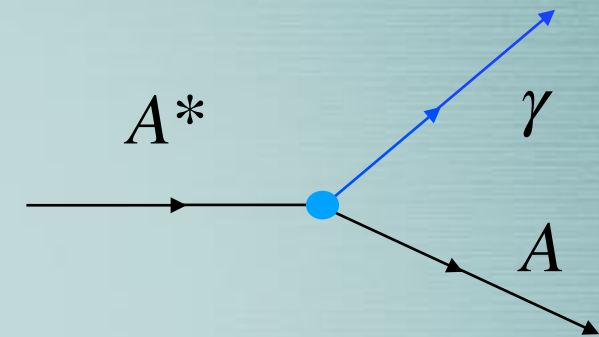
However, if you have a very intense flux of neutrinos, as in a nuclear reactor, you may observe events of the inverse beta decay process: $\bar{\nu} + p \rightarrow e^+ + n$ (Reines and Cowan, 1953).

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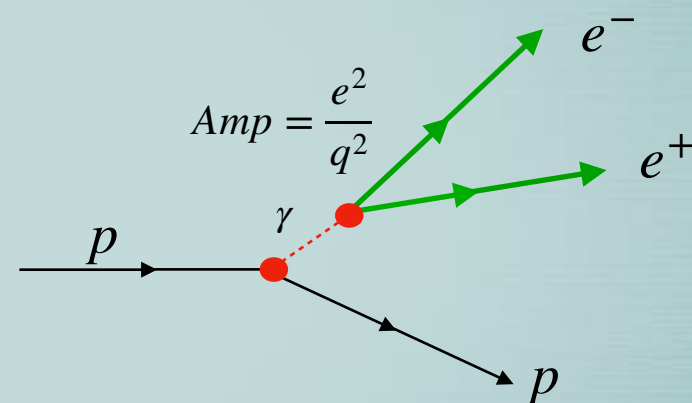
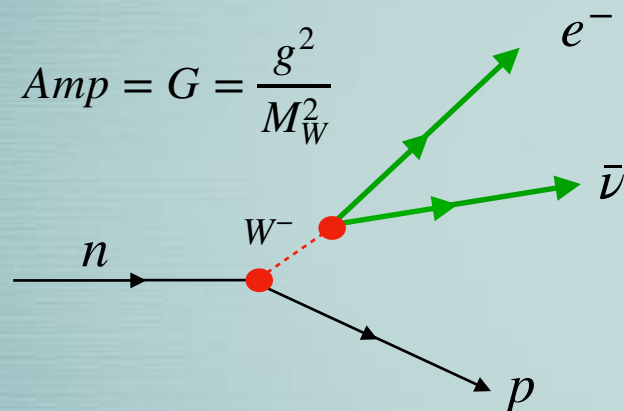
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However, if you have a very intense flux of neutrinos, as in a nuclear reactor, you may observe events of the inverse beta decay process: $\bar{\nu} + p \rightarrow e^+ + n$ (Reines and Cowan, 1953).

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

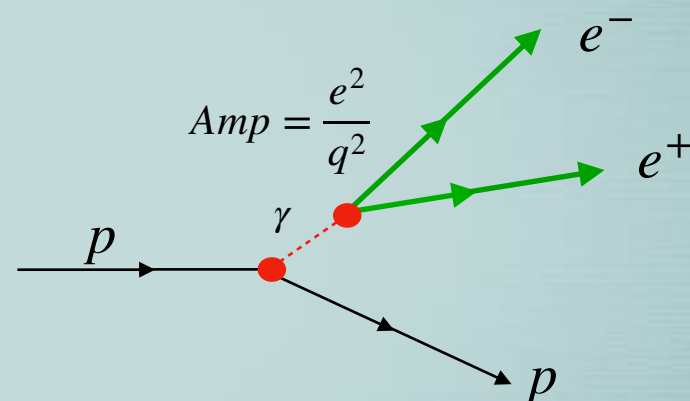
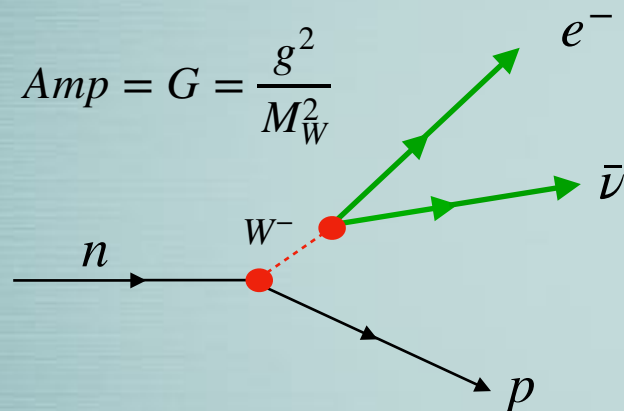
Towards a Unified Theory of Electromagnetic and Weak Interaction

- 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



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- In 1961, 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;
- the theory predicted new phenomena, like the existence of neutrino reactions in which a neutrino appears in the final state (*neutral current processes*), instead of transforming into a charged lepton as in the inverse beta decay (*charged current processes*).

1. A gauge theory of the Electromagnetic and Weak Interactions (S. Glashow, 1961)

- 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 $SU(2) \otimes U(1)$ and produced the first unified electroweak theory (for leptons only!).

• Matter: $\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}; e_R$ $\begin{matrix} \uparrow T^+ \\ \downarrow T^- \end{matrix}$

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

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

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

$Y = -1, -2$

- Y is necessary to keep Q in the gauge group

- Y commutes with $SU(2)_{\text{Weak}}$



$$G = SU(2)_{\text{Weak}} \otimes U(1)_Y$$

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

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- 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 $SU(2)_{\text{Weak}}$ singlet.
- $Q(e_R) = -1 = Y(e_R)/2 \rightarrow Y(e_R) = -2$
- Same considerations for the $\nu_\mu - \mu$ doublet

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

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

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

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

All particles are massless in the symmetry limit!

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:*

1. Can we give a mass to the IVB leaving the photon massless? (solution: Weinberg&Salam, 1967: 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 $K \rightarrow \mu^+ \mu^-$? (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).

2. The Higgs, Brout, Englert Englert Miracle

P. W. Higgs, Phys. Rev. **145** (1966) 1156.

F. Englert, R. Brout, Phys. Rev. Lett. **13** (1964) 321.:

I will follow : L. Maiani, “Electroweak Interactions,”

CRC Press, 2015, ISBN 978-0-429-15980-0

Abelian case

- Symmetry U(1)

- Introduce scalar, complex field, 2 real components:

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

- and a lagrangian invariant under global phase transformations

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

- This invariant Lagrangian is renormalizable by power counting (can you prove it?)
- Stability: $\lambda > 0$

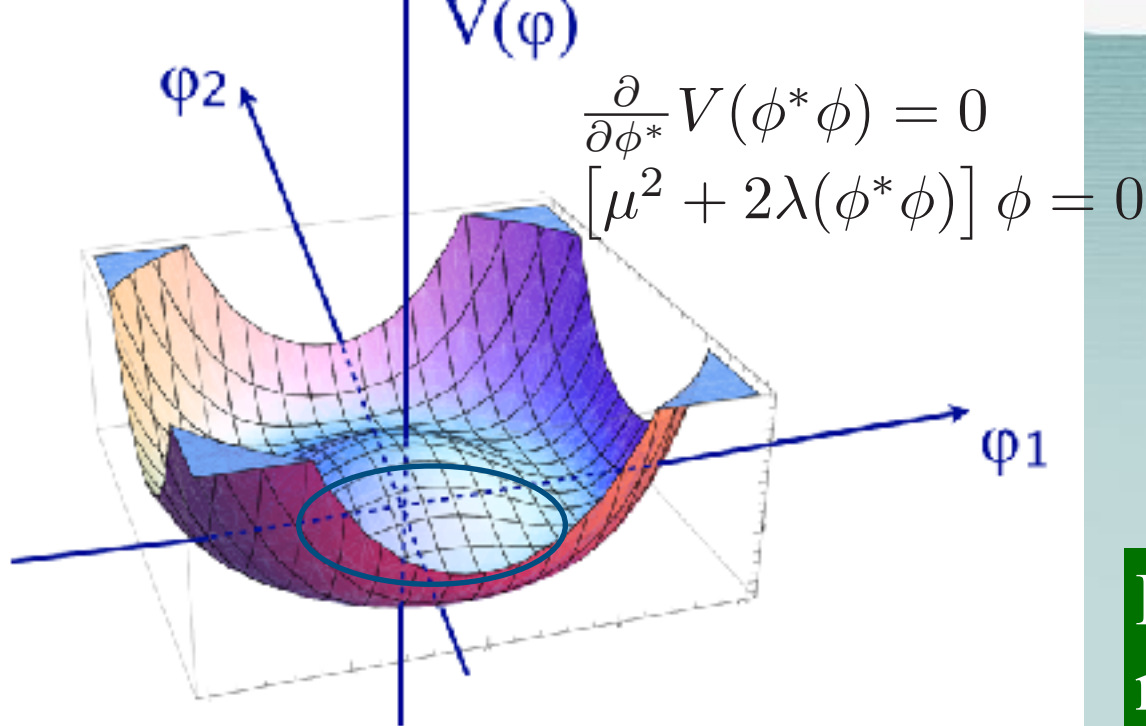
- Ground state (vacuum): minimum of H:

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

- Translationally invariant vacuum: $\phi = \text{const.}$

- therefore ϕ must be the minimum of V.

- The minimum may not be invariant under the symmetry: *spontaneous symmetry breaking*



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

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

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

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

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

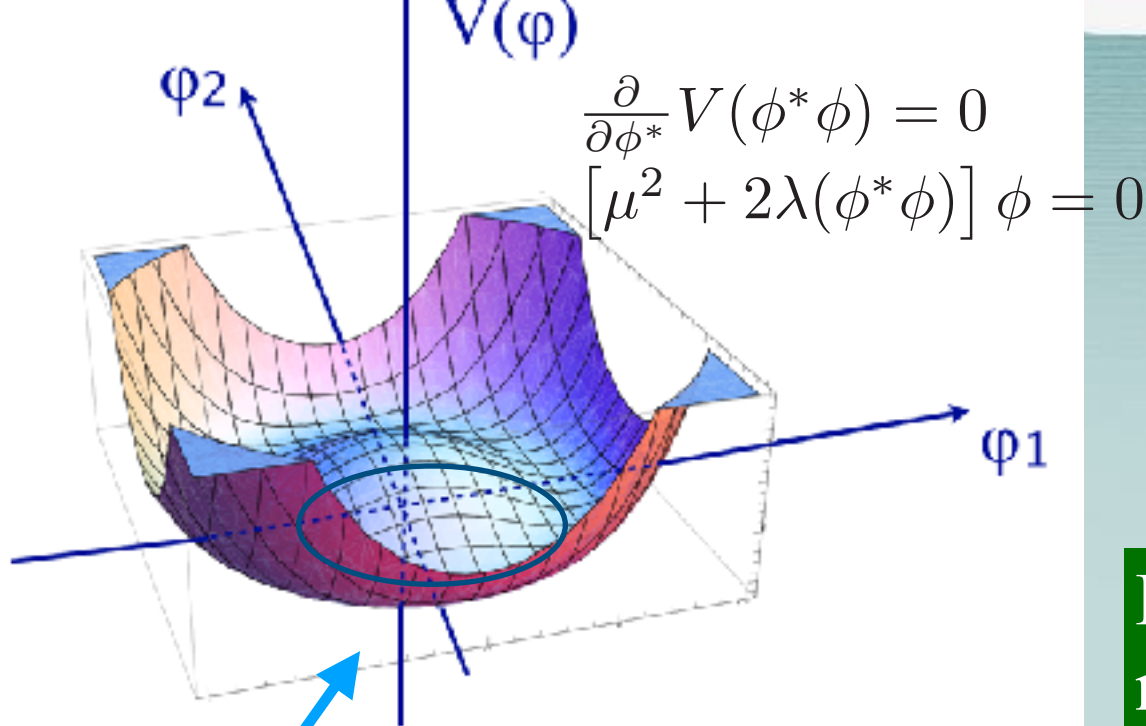
$$V(0) = C$$

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

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

What is the spectrum? Develop fields around η

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



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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:

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

- “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. Nambu 1961, J. Goldstone 1962).

Unitary gauge: the Higgs-Brout-Englert miracle

$$\phi(x) = \eta + \frac{\sigma + i\xi}{\sqrt{2}} \sim e^{i\frac{\xi}{\eta\sqrt{2}}} \left(1 + \frac{\sigma}{\sqrt{2}}\right) = U[\xi(x)]\phi_{real}$$

- with a change in parametrization we see that with a gauge transformation *we can make ϕ real and completely independent from ξ .*

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

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

$$\begin{aligned}\mathcal{L}_{loc.symm} &= \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma + g^2\eta^2 A_\mu A^\mu \left(1 + \frac{\sigma}{\eta\sqrt{2}}\right)^2 - V = \\ &= \frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma + m_\sigma^2\sigma^2) + \frac{1}{2}(2g^2\eta^2)A_\mu A^\mu + interactions\end{aligned}$$

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

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

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

- particle spectrum of the ***unbroken theory*** had two massive scalars and one massless vector
- ***spontaneous broken global symmetry***: one massless scalar (Goldstone boson) one massless vector one massive scalar
- 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!***

3. The Weinberg-Salam theory

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 try with 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:

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

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

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

- 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: $\mathcal{L} = \frac{1}{2} (\partial_\mu \xi_1 \partial^\mu \xi_1) - \frac{1}{2} (4\lambda^2) \sigma^2 + \text{interactions}$
- “interactions” are terms of order 3 or higher in the ξ s
- 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 quadratic terms in ξ^i 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: $\phi = \phi_{\text{diag}}$; $\phi_{\text{diag}}(\eta) = \phi_0$

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

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

- 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 (Higgs-Brout-Englert mechanism), $W^\pm, Z$.
- Photon remains massless.
- The 3 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: $g^A T^A A_\mu^A = g \frac{\tau^i}{2} W_\mu^i + \frac{1}{2} g' B_\mu$
- in the basis of the fields W^1, W^2, W^3, B , one obtains:
$$(\mu^2)_{ab} = M_W^2 \delta_{ab}, \quad a, b = 1, 2; \quad M_W^2 = \frac{1}{2} g^2 \eta^2$$
$$\mu^2 = M_W^2 \begin{pmatrix} g^2 & -gg' \\ -gg' & g'^2 \end{pmatrix}$$
- the W^3, B matrix has $\text{Det}(\mu^2)=0$, corresponding to the massless photon.
- Defining the physical Z and photon field as

$$Z_\mu = \cos\theta W_\mu^3 - \sin\theta B_\mu; \quad A_\mu = \sin\theta W_\mu^3 + \cos\theta B_\mu$$

one finds:

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

and

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

Currents and Fermi couplings

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

- from this, one finds easily the interaction lagrangian:

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

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

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

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

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

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

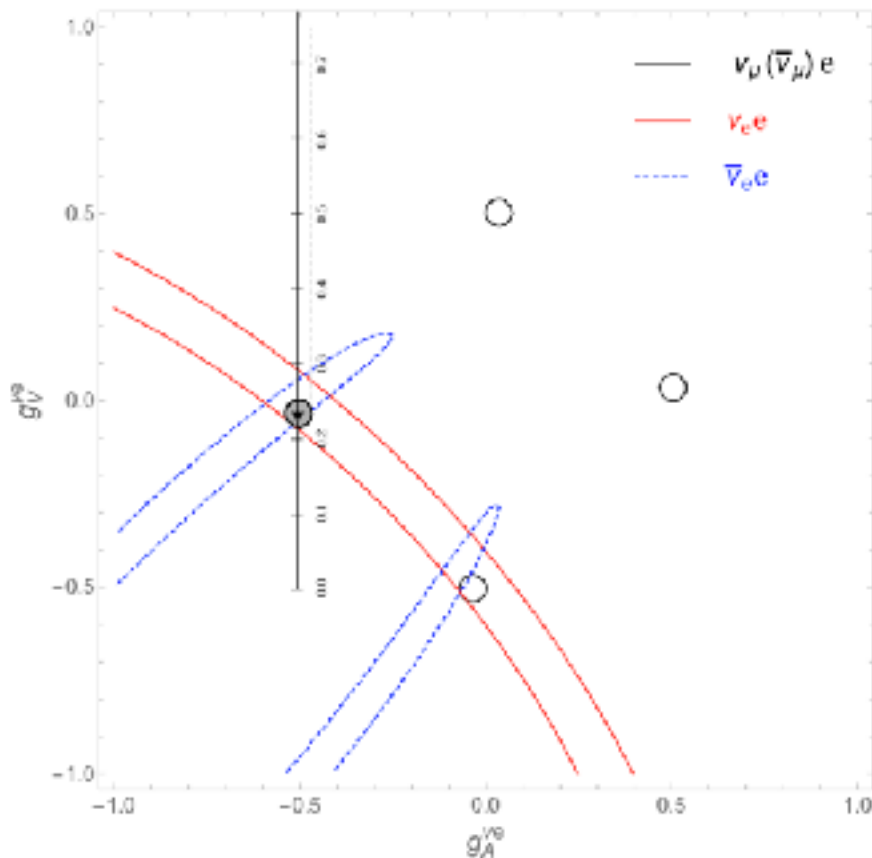
$$\frac{G}{\sqrt{2}} = \frac{g^2}{8M_W^2} \quad g_V = -\frac{1}{2} + 2 \sin^2 \theta; \quad g_A = -\frac{1}{2}$$

Note: relative normalization of neutral and charged currents is fixed

$\sin^2\theta$ from e- ν neutral current scattering

J. Erler and A. Freitas in pdgLive

M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018)



$$\sin^2\theta_Z = 0.23122$$

$$M_W = 80.0 \text{ GeV}; M_Z = 90.0 \text{ GeV}$$

Allowed contours in $g_V^{\nu e}$ vs. $g_A^{\nu e}$ from neutrino-electron scattering and the SM prediction as a function of $\sin^2\theta_Z$ (the SM best fit value $\sin^2\theta_Z = 0.23122$ is also indicated.) The $\nu_e e$ [80] and $\bar{\nu}_e e$ [81] constraints are at 1σ , while each of the four equivalent $\nu_\mu(\bar{\nu}_\mu)e$ [78–79] solutions ($g_{A,V} \rightarrow -g_{A,V}$ and $g_{A,V} \rightarrow g_{A,V}$) are at the 90% C.L. The global best fit region (shaded) almost exactly coincides with the corresponding $\nu_\mu(\bar{\nu}_\mu)e$ region.

The solution near $g_A = 0$, $g_V = -0.5$ is eliminated by $e^+e^- \rightarrow l^+l^-$ data under the weak additional assumption that the neutral current is dominated by the exchange of a single Z boson.

4. 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:

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

- In the vacuum configuration:

$$(\langle \phi^\pm \rangle_0 = 0, \langle \phi^0 \rangle_0 = \eta :$$

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

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 :

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

- We know η :

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

$$m_H^2 = 4\lambda\eta^2$$

$$m_H = \sqrt{\lambda} \ 340 \text{ GeV}$$

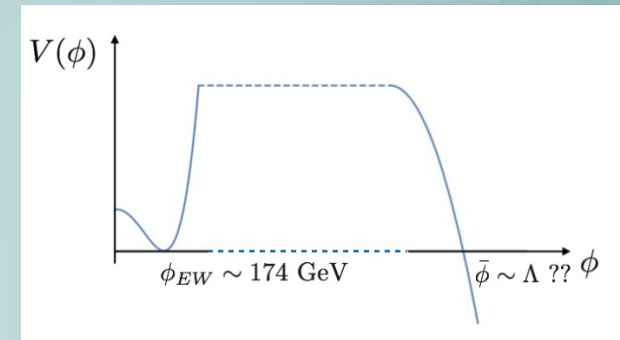
- The direct ratio between σ -VV coupling and the V mass, f mass, σ -VV, $\sigma - f\bar{f}$ and σ - σ -VV are the signatures of the Higgs mechanism.

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

Bounds to the Higgs boson mass (cont'd)

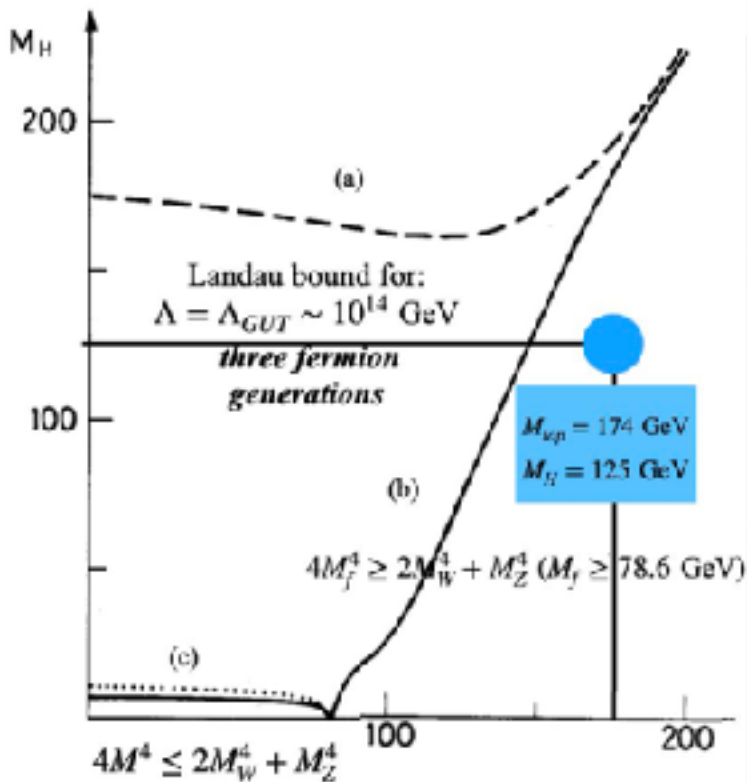
$$\beta(\lambda) = \frac{1}{16\pi^2} (4\lambda^2 - 36g_t^4 + 12g_t^2) + \text{smaller EW corr.s}$$

- For a given λ , g_t can drive it to smaller values until λ becomes negative at some energy scale $q \sim \Lambda_{\text{low}}$
- potential decreasing at value of the field $\phi \sim \Lambda_{\text{low}}$ 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 $\Lambda = M_{\text{GUT}} \sim 10^{14}$ GeV or $\Lambda = M_{\text{Planck}} \sim 10^{19}$ GeV.



- Bounds have been derived for $\Lambda = M_{\text{GUT}}$, 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:

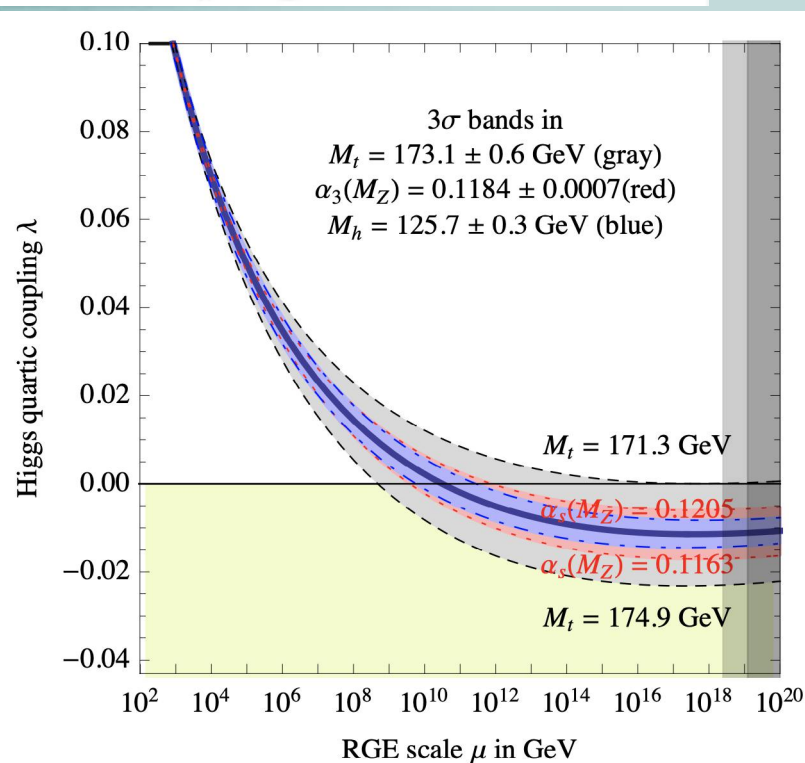
G. Altarelli and G. Isidori, Phys. Lett. **B 337** (1994) 141;
 M. Sher, Phys. Lett. **B 317** (1993) 159, **B 331** (1994) 448.
 G. Degrandi *et al.*, JHEP **1208** (2012) 098



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. Degrandi *et al.*, JHEP **1208** (2012) 098