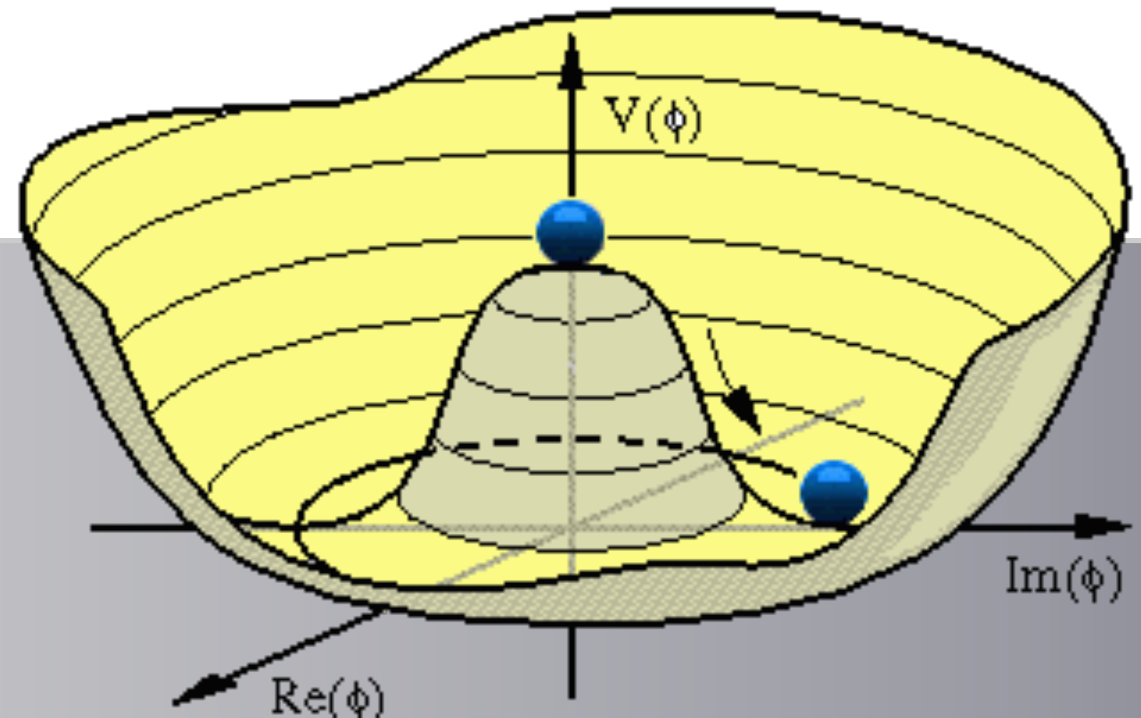
Higgs Physics

An Experimentalists Introduction ...



Reading Suggestion ...

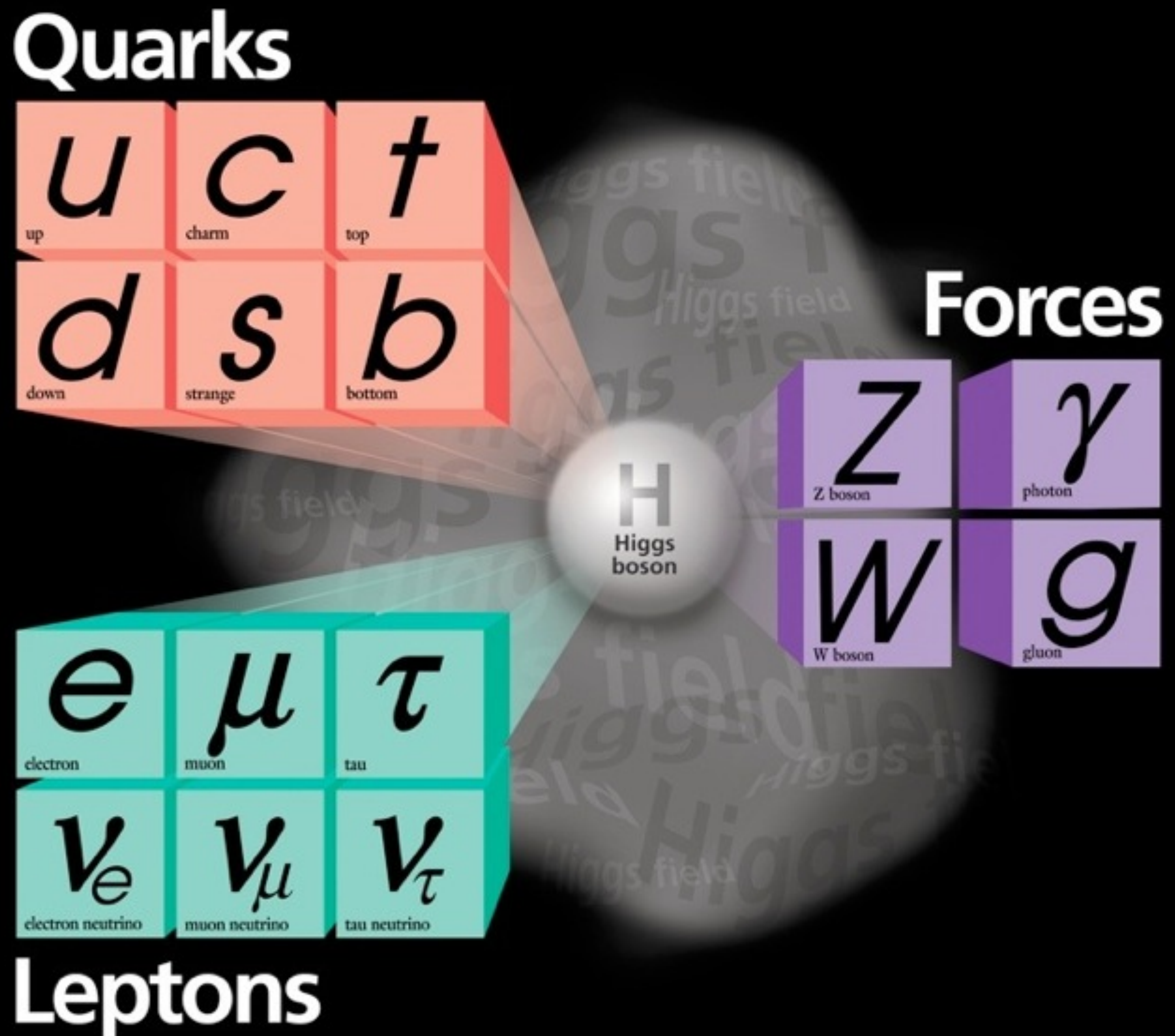
Scientific Background on the Nobel Prize in Physics 2013

THE BEH-MECHANISM, INTERACTIONS WITH SHORT RANGE FORCES AND SCALAR PARTICLES

Compiled by the Class for Physics of the Royal Swedish Academy of Sciences

The Standard Model

A particle physicist's view of the world ...



The Standard Model

A theorist's view of the world ...

Free Fields

Interaction

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}'$$

Fermions
[kinetic terms]

Mass Terms
[from Yukawa couplings]

$$\mathcal{L}_0 = \mathcal{L}_{\rm Dirac} + \mathcal{L}_{\rm mass} + \ldots$$

$$\ldots + \mathcal{L}_{\rm gauge}$$

Gauge Fields
[kinetic energy]

$$\mathcal{L}' = \mathcal{L}_{WZA} + \mathcal{L}_{{\rm gauge}/\psi}$$

Gauge Fields
[triple and quartic couplings]

Interactions
[Fermion-Boson couplings]

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm Dirac} + \mathcal{L}_{\rm mass} + \mathcal{L}_{\rm gauge} + \mathcal{L}_{{\rm gauge}/\psi} \ .$$

$$\mathcal{L}_{\rm Dirac} = i\bar{e}^i_{\rm L}\partial\!\!\!/ e^i_{\rm L} + i\bar{\nu}^i_{\rm L}\partial\!\!\!/ \nu^i_{\rm L} + i\bar{e}^i_{\rm R}\partial\!\!\!/ e^i_{\rm R} + i\bar{u}^i_{\rm L}\partial\!\!\!/ u^i_{\rm L} + i\bar{d}^i_{\rm L}\partial\!\!\!/ d^i_{\rm L} + i\bar{u}^i_{\rm R}\partial\!\!\!/ u^i_{\rm R} + i\bar{d}^i_{\rm R}\partial\!\!\!/ d^i_{\rm R} \ ;$$

$$\mathcal{L}_{\rm mass} = -v\left(\lambda^i_e \bar{e}^i_{\rm L} e^i_{\rm R} + \lambda^i_u \bar{u}^i_{\rm L} u^i_{\rm R} + \lambda^i_d \bar{d}^i_{\rm L} d^i_{\rm R} + {\rm h.c.}\right) - M_W^2 W^+_\mu W^{-\mu} - \frac{M_W^2}{2\cos^2\theta_W} Z_\mu Z^\mu \ ;$$

$$\mathcal{L}_{\rm gauge} = -\frac{1}{4}(G^a_{\mu\nu})^2 - \frac{1}{2}W^+_{\mu\nu}W^{-\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \mathcal{L}_{WZA} \ ,$$

$$\begin{aligned}
G^a_{\mu\nu} &= \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g_3 f^{abc} A^b_\mu A^c_\nu \\
W^\pm_{\mu\nu} &= \partial_\mu W^\pm_\nu - \partial_\nu W^\pm_\mu \\
Z_{\mu\nu} &= \partial_\mu Z_\nu - \partial_\nu Z_\mu \\
F_{\mu\nu} &= \partial_\mu A_\nu - \partial_\nu A_\mu \ ,
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{WZA} = \ & i g_2 \cos\theta_{\rm W}\left[\left(W^-_\mu W^+_\nu - W^-_\nu W^+_\mu\right)\partial^\mu Z^\nu + W^+_{\mu\nu}W^{-\mu}Z^\nu - W^-_{\mu\nu}W^{+\mu}Z^\nu\right] \\
& + ie\left[\left(W^-_\mu W^+_\nu - W^-_\nu W^+_\mu\right)\partial^\mu A^\nu + W^+_{\mu\nu}W^{-\mu}A^\nu - W^-_{\mu\nu}W^{+\mu}A^\nu\right] \\
& + g_2^2\cos^2\theta_{\rm W}\left(W^+_\mu W^-_\nu Z^\mu Z^\nu - W^+_\mu W^{-\mu} Z_\nu Z^\nu\right) \\
& + g_2^2\left(W^+_\mu W^-_\nu A^\mu A^\nu - W^+_\mu W^{-\mu} A_\nu A^\nu\right) \\
& + g_2 e\cos\theta_{\rm W}\left[W^+_\mu W^-_\nu\left(Z^\mu A^\nu + Z^\nu A^\mu\right) - 2W^+_\mu W^{-\mu} Z_\nu A^\nu\right] \\
& + \frac{1}{2}g_2^2\left(W^+_\mu W^-_\nu\right)\left(W^{+\mu}W^{-\nu} - W^{+\nu}W^{-\mu}\right) \ ;
\end{aligned}$$

$$\mathcal{L}_{{\rm gauge}/\psi} = -g_3 A^a_\mu J^{\mu a}_{(3)} - g_2\left(W^+_\mu J^\mu_{W^+} + W^-_\mu J^\mu_{W^-} + Z_\mu J^\mu_Z\right) - eA_\mu J^\mu_A \ ,$$

$$\begin{aligned}
J^{\mu a}_{(3)} &= \bar{u}^i\gamma^\mu T^a_{(3)} u^i + \bar{d}^i\gamma^\mu T^a_{(3)} d^i \\
J^\mu_{W^+} &= \frac{1}{\sqrt{2}}\left(\bar{\nu}^i_{\rm L}\gamma^\mu e^i_{\rm L} + V^{ij}\bar{u}^i_{\rm L}\gamma^\mu d^j_{\rm L}\right) \\
J^\mu_{W^-} &= (J^\mu_{W^+})^* \\
J^\mu_Z &= \frac{1}{\cos\theta_{\rm W}}\left[\frac{1}{2}\bar{\nu}^i_{\rm L}\gamma^\mu\nu^i_{\rm L} + \left(-\frac{1}{2} + \sin^2\theta_{\rm W}\right)\bar{e}^i_{\rm L}\gamma^\mu e^i_{\rm L} + (\sin^2\theta_{\rm W})\bar{e}^i_{\rm R}\gamma^\mu e^i_{\rm R}\right. \\
& \quad + \left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_{\rm W}\right)\bar{u}^i_{\rm L}\gamma^\mu u^i_{\rm L} + \left(-\frac{2}{3}\sin^2\theta_{\rm W}\right)\bar{u}^i_{\rm R}\gamma^\mu u^i_{\rm R} \\
& \quad \left. + \left(-\frac{1}{2} + \frac{1}{3}\sin^2\theta_{\rm W}\right)\bar{d}^i_{\rm L}\gamma^\mu d^i_{\rm L} + \left(\frac{1}{3}\sin^2\theta_{\rm W}\right)\bar{d}^i_{\rm R}\gamma^\mu d^i_{\rm R}\right] \\
J^\mu_A &= (-1)\bar{e}^i\gamma^\mu e^i + \left(\frac{2}{3}\right)\bar{u}^i\gamma^\mu u^i + \left(-\frac{1}{3}\right)\bar{d}^i\gamma^\mu d^i \ .
\end{aligned}$$

+ Higgs terms

From the Lagrangian to Cross Sections ...

$$\sigma \sim \langle\, f\, |\mathbf{S}|\, i\, \rangle^{\,2}$$

Inelastic
Cross Section
[for |i⟩ ≠ |f⟩]

$$[\mathrm{Def.}:\ |\, t = +\infty\,\rangle \equiv \mathbf{S}|\, t = -\infty\,\rangle\,]$$

Time Evolution
from Schrödinger-Equation
[Dirac picture]

$$|\, t\,\rangle = |\, t_0\,\rangle - i\int_{t_0}^{t} \mathrm{d}t'\, \mathbf{H}'(t')|\, t'\,\rangle$$

$$\mathbf{H}'(t) = -\int \mathcal{L}'(x,t)\, \mathrm{d}^3x$$

Lagrangian
of interaction

$$\langle\, f\, |\mathbf{S}|\, i\,\rangle \cong \delta_{fi} - i\int_{-\infty}^{\infty} \mathrm{d}t' \langle\, f\, |\mathbf{H}'(t')|\, i\,\rangle$$

➥ Feynman rules

The SM Lagrangian [massless particles]

kinetic & self-coupling of gauge bosons

kinetic energy of fermions

interaction between fermions & fields

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi + e\bar{\psi}\gamma^{\mu}A_{\mu}\psi$$

SM Lagrangian without Higgs

where:

$$eA_{\mu} = \frac{g_s}{2}\lambda_{\nu}G^{\nu}_{\mu} + \frac{g}{2}\vec{\tau}\,\vec{W}_{\mu} + \frac{g'}{2}Y B_{\mu}$$

$$F_{\mu\nu}F^{\mu\nu} = G_{\mu\nu}G^{\mu\nu} + W_{\mu\nu}W^{\mu\nu} + B_{\mu\nu}B^{\mu\nu}$$

But: $SU(2)_L \times U(1)_Y$ symmetry forbids „ad hoc“ introduction of extra masses terms:

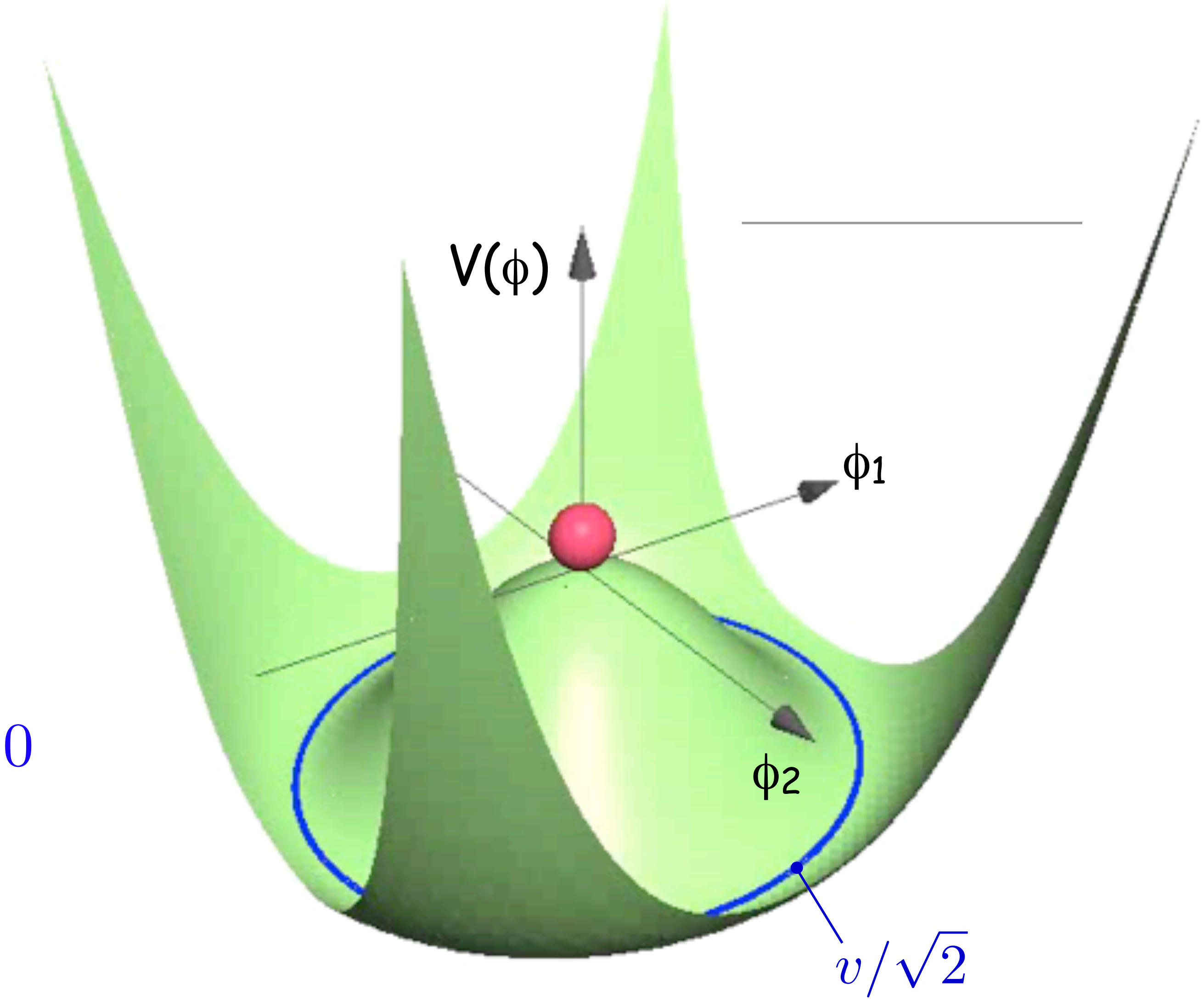
Fermions: $m\bar{\psi}\psi$

Bosons: $m^2 A_{\mu} A^{\mu}$

destroy gauge invariance !

But: particles do have mass

The Higgs Mechanism



Introduce:
New doublet of complex scalar fields
[4 degrees of freedom; 'mexican hat' potential]

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

$$\text{with} \;\; \mu, \lambda > 0$$

Lagrangian of scalar field:

$$\mathcal{L}_\phi = (\partial_\mu \phi^\dagger)(\partial^\mu \phi) - V(\phi)$$

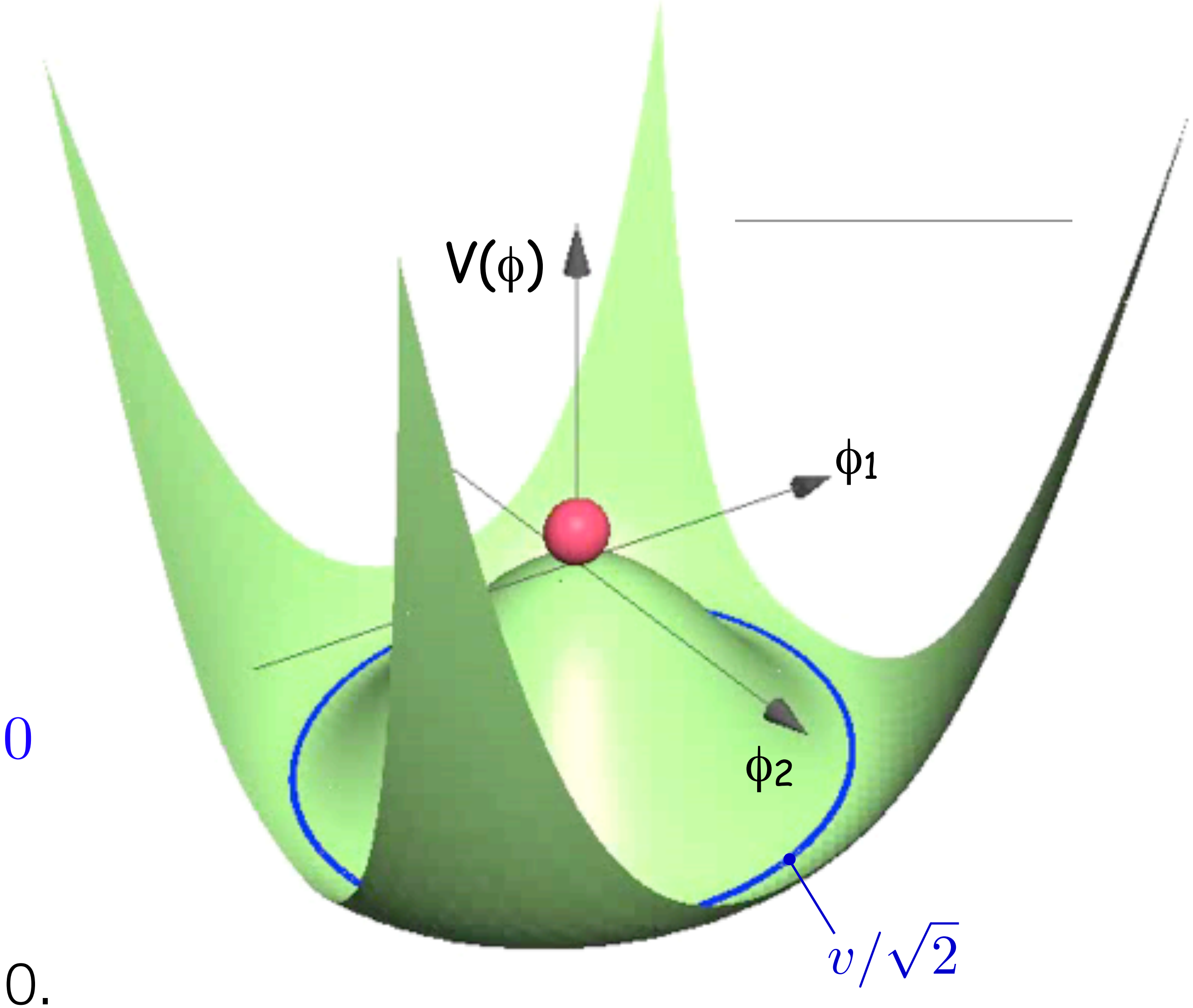
Coupling to bosons via transition to covariant derivative.
Coupling to fermions via "ad-hoc" introduction of "Yukawa" coupling.

$$\mathcal{L}_\phi = (D_\mu \phi^\dagger)(D^\mu \phi) - V(\phi) \quad \text{with} \quad D_\mu = \partial_\mu + ieA_\mu$$

$$\mathcal{L}_{\text{Yuk}} = c_f(\bar{\psi}_L \psi_R \phi + \bar{\psi}_R \psi_L \phi)$$

Introduction into SM Lagrangian maintains invariance under $SU(2)_L \times U(1)_Y$ gauge transformation

The Higgs Mechanism



Introduce:
New doublet of complex scalar fields
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with $\mu, \lambda > 0$

Spontaneous symmetry breaking:

System falls in to minimum of V at $\phi \neq 0$.

This results in:

- Three massless excitations along valley ➛ 3 longitudinal d.o.f. for $W^\pm$ and Z
- One massive excitation out of valley ➛ 1 d.o.f. for „physical" Higgs boson

Higgs field has two components: ϕ = "v + H".

1. omnipresent, constant background condensate v = 246 GeV (from $G_F = (2v^2)^{-½}$)
2. Higgs boson H with unknown mass $M_H = \mu\cdot\sqrt{2} = (2\lambda)^{½}\cdot v$

Mass generation and Higgs couplings

Yields Higgs-Boson couplings

Contains Higgs self-couplings

$$\mathcal{L}_\phi = (D_\mu \phi^\dagger)(D^\mu \phi) - V(\phi) \quad \text{with} \quad D_\mu = \partial_\mu + ieA_\mu$$

$$\mathcal{L}_{\text{Yuk}} = c_f(\bar{\psi}_L \psi_R \phi + \bar{\psi}_R \psi_L \phi)$$

Higgs-fermion coupling

$$M_W = gv/2$$

$$M_Z = \sqrt{g^2 + g'^2}\, v/2$$

$$M_H = \mu\sqrt{2} = \sqrt{2\lambda}\, v$$

Substitute:

$$\phi \to \phi' = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v+H) \end{pmatrix}$$

$$\mathcal{L}_{\text{Yuk}} = (\sqrt{2})^{-1} \cdot \left[\, c_f(\bar{\psi}_L \psi_R H + \bar{\psi}_R \psi_L H) + c_f v(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L) \,\right]$$

$$= (\sqrt{2})^{-1} \cdot \left[\, c_f(\bar{\psi}_L \psi_R H + \bar{\psi}_R \psi_L H) + m_f \bar{\psi}\psi \,\right]$$

Mass generation and Higgs couplings

Interaction with „ether" v=247 GeV:

$M_V \sim gv$ (Gauge coupling)
$m_f \sim g_f v$ (Yukawa coupling)

$$\left(\frac{1}{q^2}\right) \quad \left(\frac{gv}{2}\right)^2\left(\frac{1}{q^2}\right)^2 \quad \left(\frac{gv}{2}\right)^4\left(\frac{1}{q^2}\right)^3$$

... =

$$\frac{1}{q^2 - M^2} \quad \text{where} \quad M = \frac{gv}{2}$$

Interaction with Higgs boson H:

Fermions: $g_f \sim m_f/v$
W/Z bosons: $g_V \sim M_V^2/v = g^2 \cdot v$