

Phenomenological Issues in Beyond the Standard Model

- The Structure of the Standard Model
- The MSSM
- Testing the Standard Model
- Neutrino Physics
- Beyond the MSSM

The Structure of the Standard Model

Remarkably successful gauge theory of the microscopic interactions.

1. The Standard Model Lagrangian

2. Spontaneous Symmetry Breaking

3. The Gauge Interactions

(a) The Charged Current

(b) QED

(c) The Neutral Current

(d) Gauge Self-interactions

4. Problems With the Standard Model

(See “Structure Of The Standard Model,” hep-ph/0304186)

Gauge Transformations

$$\begin{aligned}\Phi &\rightarrow \Phi' \equiv U\Phi \\ \vec{A}_\mu \cdot \vec{L} &\rightarrow \vec{A}'_\mu \cdot \vec{L} \equiv U\vec{A}_\mu \cdot \vec{L}U^{-1} + \frac{i}{g}(\partial_\mu U)U^{-1} \\ U &= e^{i\vec{\beta}\cdot\vec{L}}\end{aligned}$$

where Φ is an n component representation vector for fermions or spin-0, L^i is the $n \times n$ dimensional representation matrix for the i^{th} generator ($i = 1, \dots, N$), β^i ($i = 1, \dots, N$) is an arbitrary differentiable real function of space and time, and A_μ are N Hermitian gauge fields.

The Standard Model Lagrangian

Group: $SU(3) \times SU(2) \times U(1)$

Gauge couplings: g_s (QCD); g, g' (electroweak)

Generators:

$SU(3)$ (QCD): $L^i, i = 1, \dots, 8$

$SU(2)$: $T^i, i = 1, 2, 3$

$U(1)$: Y (weak hypercharge)

Gauge bosons:

$SU(3)$ (QCD): $G_\mu^i, i = 1, \dots, 8$

$SU(2)$: $W_\mu^i, i = 1, 2, 3$

$U(1)$: B_μ

Quarks/leptons:

Chiral Projections: $\psi_{L(R)} \equiv \frac{1}{2}(1 \mp \gamma_5)\psi$

(Chirality = helicity up to $O(m/E)$)

L -doublets:

$$q_{mL}^0 = \begin{pmatrix} u_m^0 \\ d_m^0 \end{pmatrix}_L \quad l_{mL}^0 = \begin{pmatrix} \nu_m^0 \\ e_m^{-0} \end{pmatrix}_L$$

R -singlets: $u_{mR}^0, d_{mR}^0, e_{mR}^{-0}, (\nu_{mR}^0)$

($F \geq 3$ families; $m = 1 \dots F$ = family index; 0 = weak eigenstates (definite $SU(2)$ rep.), mixtures of mass eigenstates (flavors); quark color indices $\alpha = r, g, b$ suppressed (e.g., $u_{m\alpha L}^0$).

Higgs: Complex scalar doublet $\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$

$U(1)_Q$: Electric charge generator $Q = T^3 + Y$

$$Y_{q_L} = \frac{1}{6}, \quad Y_{l_L} = -\frac{1}{2}, \quad Y_{\psi_R} = q_\psi, \quad Y_\varphi = +\frac{1}{2}$$

Lagrangian: $\mathcal{L} = \mathcal{L}_{SU(3)} + \mathcal{L}_{SU(2) \times U(1)}$

Quantum Chromodynamics (QCD)

$$\mathcal{L}_{SU(3)} = -\frac{1}{4} F_{\mu\nu}^i F^{i\mu\nu} + \sum_r \bar{q}_{r\alpha} i \not{D}_\beta^\alpha q_r^\beta$$

F^2 term leads to three and four-point gluon self-interactions.

$$F_{\mu\nu}^i = \partial_\mu G_\nu^i - \partial_\nu G_\mu^i - g_s f_{ijk} G_\mu^j G_\nu^k$$

is field strength tensor for the gluon fields G_μ^i , $i = 1, \dots, 8$, $g_s =$ QCD gauge coupling constant. No gluon masses.

Structure constants f_{ijk} ($i, j, k = 1, \dots, 8$), defined by

$$[\lambda^i, \lambda^j] = 2i f_{ijk} \lambda^k$$

where λ^i are the Gell-Mann matrices.

$$\lambda^i = \begin{pmatrix} \tau^i & 0 \\ 0 & 0 \end{pmatrix}, \quad i = 1, 2, 3$$

$$\lambda^4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

$$\lambda^6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

$$\lambda^8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

$$\lambda^5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}$$

$$\lambda^7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix}$$

The SU_3 (Gell-Mann) matrices.

Quark interactions given by $\bar{q}_{r\alpha} i \not{D}_\beta^\alpha q_r^\beta$

$q_r = r^{\text{th}}$ quark flavor; $\alpha, \beta = 1, 2, 3$ are color indices; Gauge covariant derivative

$$D_{\mu\beta}^\alpha = (D_\mu)_{\alpha\beta} = \partial_\mu \delta_{\alpha\beta} + ig_s G_\mu^i L_{\alpha\beta}^i,$$

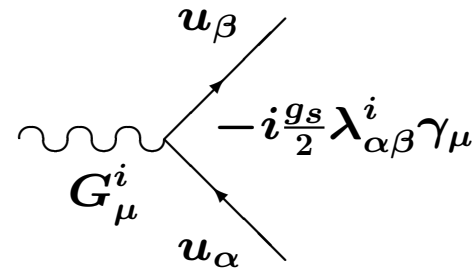
for triplet representation matrices $L^i = \lambda^i/2$.

Quark color interactions:

Diagonal in flavor

Off diagonal in color

Purely vector (parity conserving)



Bare quark mass allowed by QCD, but forbidden by the chiral symmetry of $\mathcal{L}_{SU(2) \times U(1)}$ (generated by spontaneous symmetry breaking)

Additional ghost and gauge-fixing terms

Can add (unwanted) CP-violating term $\mathcal{L}_\theta = \frac{\theta g_s^2}{32\pi^2} F_{\mu\nu}^i \tilde{F}^{i\mu\nu}$, $\tilde{F}^{i\mu\nu} \equiv \frac{1}{2} \epsilon^{\mu\nu\alpha\beta} F_{\alpha\beta}^i$

QCD now very well established

- Short distance behavior (asymptotic freedom)
- Confinement, light hadron spectrum (lattice)
- Approximate global $SU(3)_L \times SU(3)_R$ symmetry and breaking (π, K, η are pseudogoldstone bosons)
- Unique field theory of strong interactions

The Electroweak Sector

$$\mathcal{L}_{SU_2 \times U_1} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_\varphi + \mathcal{L}_f + \mathcal{L}_{\text{Yukawa}}$$

Gauge part

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}F_{\mu\nu}^i F^{\mu\nu i} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

Field strength tensors

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

$$F_{\mu\nu} = \partial_\mu W_\nu^i - \partial_\nu W_\mu^i - g\epsilon_{ijk}W_\mu^j W_\nu^k$$

$g(g')$ is the SU_2 (U_1) gauge coupling; ϵ_{ijk} is the totally antisymmetric symbol

Three and four-point self-interactions for the W_i

B and W_3 will mix to form γ , Z

Scalar part

$$\mathcal{L}_\varphi = (D^\mu \varphi)^\dagger D_\mu \varphi - V(\varphi)$$

where $\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$. Gauge covariant derivative:

$$D_\mu \varphi = \left(\partial_\mu + ig \frac{\tau^i}{2} W_\mu^i + \frac{ig'}{2} B_\mu \right) \varphi$$

where τ^i are the Pauli matrices

Three and four-point interactions between the gauge and scalar fields

Higgs potential

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

Allowed by renormalizability and gauge invariance

Spontaneous symmetry breaking for $\mu^2 < 0$

Vacuum stability: $\lambda > 0$.

Quartic self-interactions

Fermion part (F families)

$$\mathcal{L}_F = \sum_{m=1}^F (\bar{q}_{mL}^0 i \not{D} q_{mL}^0 + \bar{l}_{mL}^0 i \not{D} l_{mL}^0 + \bar{u}_{mR}^0 i \not{D} u_{mR}^0 + \bar{d}_{mR}^0 i \not{D} d_{mR}^0 + \bar{e}_{mR}^0 i \not{D} e_{mR}^0)$$

L -doublets

$$q_{mL}^0 = \begin{pmatrix} u_m^0 \\ d_m^0 \end{pmatrix}_L \quad l_{mL}^0 = \begin{pmatrix} \nu_m^0 \\ e_m^{-0} \end{pmatrix}_L$$

R -singlets

$$u_{mR}^0, d_{mR}^0, e_{mR}^{-0}$$

Different (chiral) L and R representations lead to parity violation
(maximal for $SU(2)$)

Fermion mass terms forbidden by chiral symmetry

Can add gauge singlet ν_{mR}^0 for Dirac neutrino mass term

Gauge covariant derivatives

$$D_\mu q_{mL}^0 = \left(\partial_\mu + \frac{ig}{2} \tau^i W_\mu^i + i\frac{g'}{6} B_\mu \right) q_{mL}^0$$

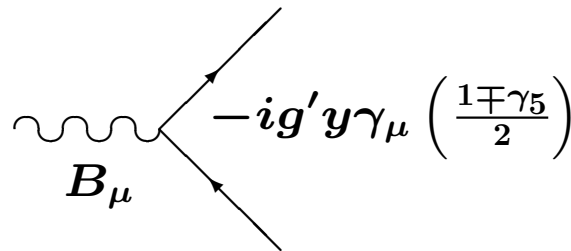
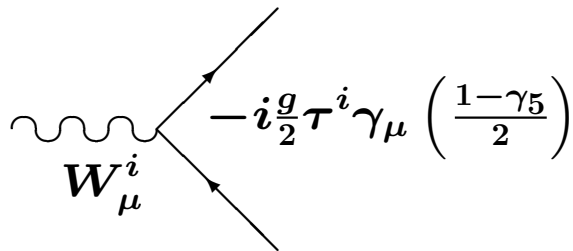
$$D_\mu l_{mL}^0 = \left(\partial_\mu + \frac{ig}{2} \tau^i W_\mu^i - i\frac{g'}{2} B_\mu \right) l_{mL}^0$$

$$D_\mu u_{mR}^0 = \left(\partial_\mu + i\frac{2}{3} g' B_\mu \right) u_{mR}^0$$

$$D_\mu d_{mR}^0 = \left(\partial_\mu - i\frac{g'}{3} B_\mu \right) d_{mR}^0$$

$$D_\mu e_{mR}^0 = \left(\partial_\mu - ig' B_\mu \right) e_{mR}^0$$

Read off W and B couplings to fermions



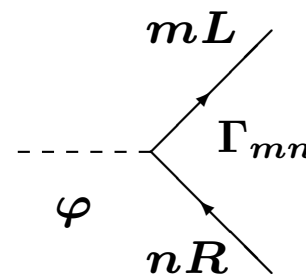
Yukawa couplings (couple L to R)

$$\begin{aligned}
 -\mathcal{L}_{\text{Yukawa}} = & \sum_{m,n=1}^F \left[\Gamma_{mn}^u \bar{q}_{mL}^0 \tilde{\varphi} u_{mR}^0 + \Gamma_{mn}^d \bar{q}_{mL}^0 \varphi d_{nR}^0 \right. \\
 & \left. + \Gamma_{mn}^e \bar{l}_{mn}^0 \varphi e_{nR}^0 \left(+ \Gamma_{mn}^\nu \bar{l}_{mL}^0 \tilde{\varphi} \nu_{mR}^0 \right) \right] + \text{H.C.}
 \end{aligned}$$

Γ_{mn} are completely arbitrary Yukawa matrices, which determine fermion masses and mixings

d, e terms require doublet $\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$ with $Y_\varphi = 1/2$

u (and ν) terms require doublet $\Phi = \begin{pmatrix} \Phi^0 \\ \Phi^- \end{pmatrix}$ with $Y_\Phi = -1/2$



In $SU(2)$ the 2 and 2^* are similar $\Rightarrow \tilde{\varphi} \equiv i\tau^2\varphi^\dagger = \begin{pmatrix} \varphi^{0\dagger} \\ -\varphi^- \end{pmatrix}$
transforms as a 2 with $Y_{\tilde{\varphi}} = -\frac{1}{2} \Rightarrow$ only one doublet needed.

Does not generalize to $SU(3)$, most extra $U(1)'$, supersymmetry, etc \Rightarrow need two doublets.

(Does generalize to $SU(2)_L \times SU(2)_R \times U(1)$)

Spontaneous Symmetry Breaking

Gauge invariance implies massless gauge bosons and fermions

Weak interactions short ranged \Rightarrow spontaneous symmetry breaking for mass; also for fermions

Color confinement for QCD \Rightarrow gluons remain massless

Allow classical (ground state) expectation value for Higgs field

$$v = \langle 0|\varphi|0\rangle = \text{constant}$$

$\partial_\mu v \neq 0$ increases energy, but important for monopoles, strings, domain walls

Minimize $V(v)$ to find v and quantize $\varphi' = \varphi - v$

$SU(2) \times U(1)$: introduce Hermitian basis

$$\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}}(\varphi_1 - i\varphi_2) \\ \frac{1}{\sqrt{2}}(\varphi_3 - i\varphi_4) \end{pmatrix},$$

where $\varphi_i = \varphi_i^\dagger$.

$$V(\varphi) = \frac{1}{2}\mu^2 \left(\sum_{i=1}^4 \varphi_i^2 \right) + \frac{1}{4}\lambda \left(\sum_{i=1}^4 \varphi_i^2 \right)^2$$

is O_4 invariant.

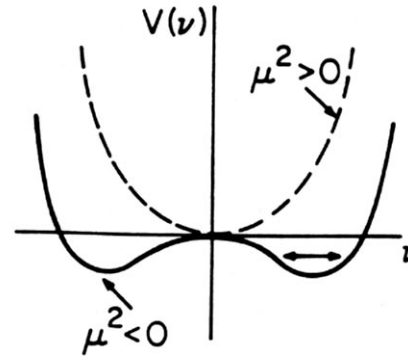
w.l.o.g. choose $\langle 0|\varphi_i|0\rangle = 0$, $i = 1, 2, 4$ and $\langle 0|\varphi_3|0\rangle = \nu$

$$V(\varphi) \rightarrow V(v) = \frac{1}{2}\mu^2\nu^2 + \frac{1}{4}\lambda\nu^4$$

For $\mu^2 < 0$, minimum at

$$V'(\nu) = \nu(\mu^2 + \lambda\nu^2) = 0$$

$$\Rightarrow \nu = (-\mu^2/\lambda)^{1/2}$$



SSB for $\mu^2 = 0$ also; must consider loop corrections

$\varphi \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu \end{pmatrix} \equiv v \Rightarrow$ the generators L^1 , L^2 , and $L^3 - Y$ spontaneously broken, $L^1 v \neq 0$, etc ($L^i = \frac{\tau^i}{2}$, $Y = \frac{1}{2}I$)

$Qv = (L^3 + Y)v = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} v = 0 \Rightarrow U(1)_Q$ unbroken \Rightarrow
 $SU(2) \times U(1)_Y \rightarrow U(1)_Q$

Quantize around classical vacuum

- Kibble transformation: introduce new variables ξ^i for rolling modes

$$\varphi = \frac{1}{\sqrt{2}} e^{i \sum \xi^i L^i} \begin{pmatrix} 0 \\ \nu + H \end{pmatrix}$$

- $H = H^\dagger$ is the Higgs scalar
- No potential for $\xi^i \Rightarrow$ massless Goldstone bosons for global symmetry
- Disappear from spectrum for gauge theory (“eaten”)
- Display particle content in unitary gauge

$$\varphi \rightarrow \varphi' = e^{-i \sum \xi^i L^i} \varphi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu + H \end{pmatrix}$$

+ corresponding transformation on gauge fields

Rewrite Lagrangian in New Vacuum

Higgs covariant kinetic energy terms

$$\begin{aligned}(D_\mu\varphi)^\dagger D^\mu\varphi &= \frac{1}{2}(0 \ \nu) \left[\frac{g}{2}\tau^i W_\mu^i + \frac{g'}{2}B_\mu \right]^2 \begin{pmatrix} 0 \\ \nu \end{pmatrix} + H \text{ terms} \\ &\rightarrow M_W^2 W^{+\mu} W_\mu^- + \frac{M_Z^2}{2} Z^\mu Z_\mu \\ &+ H \text{ kinetic energy and gauge interaction terms}\end{aligned}$$

Mass eigenstate bosons: W , Z , and A (photon)

$$\begin{aligned}W^\pm &= \frac{1}{\sqrt{2}}(W^1 \mp iW^2) \\ Z &= -\sin\theta_W B + \cos\theta_W W^3 \\ A &= \cos\theta_W B + \sin\theta_W W^3\end{aligned}$$

Masses

$$M_W = \frac{g\nu}{2}, \quad M_Z = \sqrt{g^2 + g'^2} \frac{\nu}{2} = \frac{M_W}{\cos \theta_W}, \quad M_A = 0$$

(Goldstone scalar transformed into longitudinal components of W^\pm, Z)

Weak angle: $\tan \theta_W \equiv g'/g$

Will show: Fermi constant $G_F/\sqrt{2} \sim g^2/8M_W^2$, where $G_F = 1.16639(2) \times 10^{-5} \text{ GeV}^{-2}$ from muon lifetime

Electroweak scale

$$\nu = 2M_W/g \simeq (\sqrt{2}G_F)^{-1/2} \simeq 246 \text{ GeV}$$

Will show: $g = e / \sin \theta_W$, where $\alpha = e^2 / 4\pi \sim 1 / 137.036 \Rightarrow$

$$M_W = M_Z \cos \theta_W \sim \frac{(\pi\alpha / \sqrt{2}G_F)^{1/2}}{\sin \theta_W}$$

Weak neutral current: $\sin^2 \theta_W \sim 0.23 \Rightarrow M_W \sim 78 \text{ GeV}$, and
 $M_Z \sim 89 \text{ GeV}$ (increased by $\sim 2 \text{ GeV}$ by loop corrections)

Discovered at CERN: UA1 and UA2, 1983

Current:

$$M_Z = 91.1876 \pm 0.0021$$

$$M_W = 80.449 \pm 0.034$$

The Higgs Scalar H

Gauge interactions: $ZZH, ZZH^2, W^+W^-H, W^+W^-H^2$

$$\varphi \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu + H \end{pmatrix}$$

$$\begin{aligned} \mathcal{L}_\varphi &= (D^\mu \varphi)^\dagger D_\mu \varphi - V(\varphi) \\ &= \frac{1}{2} (\partial_\mu H)^2 + M_W^2 W^{\mu+} W_\mu^- \left(1 + \frac{H}{\nu}\right)^2 \\ &+ \frac{1}{2} M_Z^2 Z^\mu Z_\mu \left(1 + \frac{H}{\nu}\right)^2 - V(\varphi) \end{aligned}$$

Higgs potential:

$$\begin{aligned} V(\varphi) &= +\mu^2\varphi^\dagger\varphi + \lambda(\varphi^\dagger\varphi)^2 \\ &\rightarrow -\frac{\mu^4}{4\lambda} - \mu^2 H^2 + \lambda\nu H^3 + \frac{\lambda}{4} H^4 \end{aligned}$$

Fourth term: Quartic self-interaction

Third: Induced cubic self-interaction

Second: (Tree level) H mass-squared,

$$M_H = \sqrt{-2\mu^2} = \sqrt{2\lambda\nu}$$

No a priori constraint on λ except vacuum stability ($\lambda > 0 \Rightarrow 0 < M_H < \infty$), but

t quark loops destabilize vacuum unless $M_H \gtrsim 115$ GeV

Strong coupling for $\lambda \gtrsim 1 \Rightarrow M_H \gtrsim 1$ TeV

Triviality: running λ should not diverge below scale Λ at which theory breaks down \Rightarrow

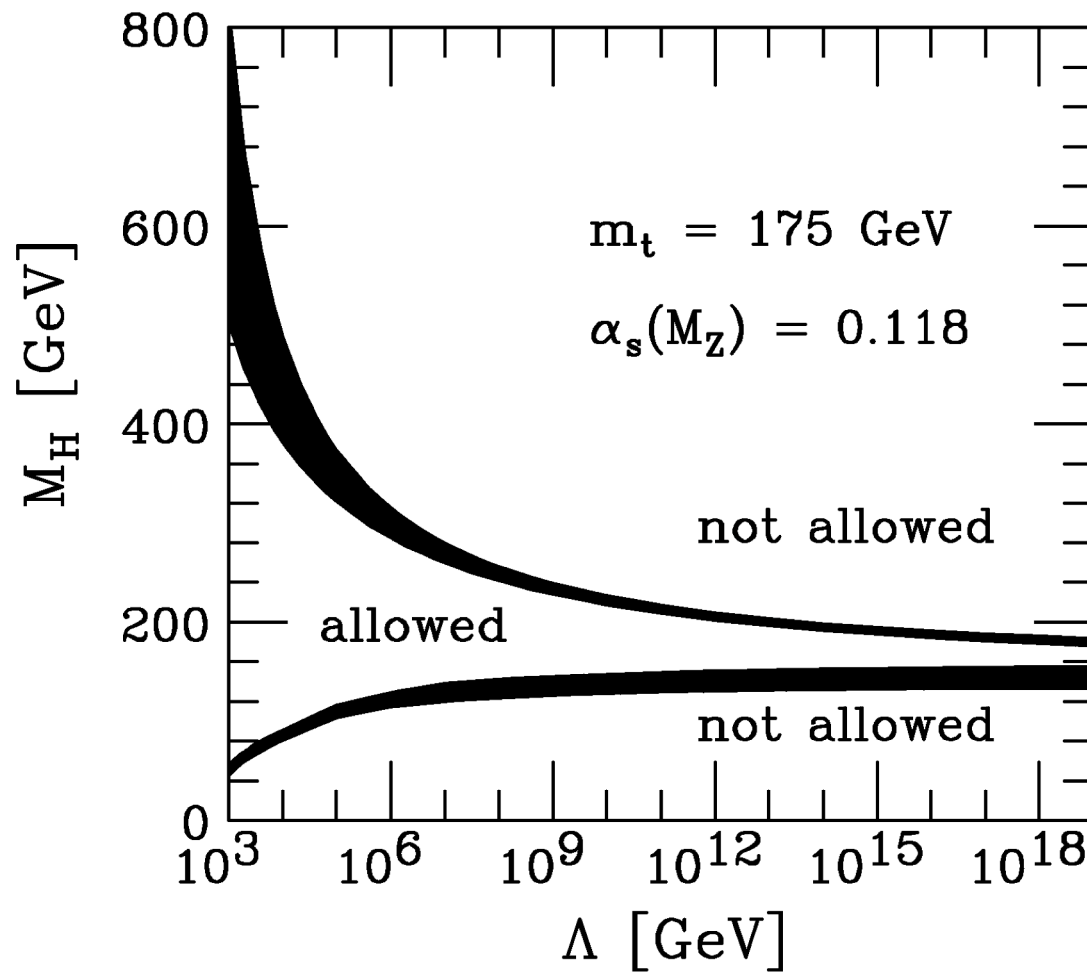
$$M_H < \begin{cases} O(200) \text{ GeV}, & \Lambda \sim M_P = G_N^{-1/2} \sim 10^{19} \text{ GeV} \\ O(750) \text{ GeV}, & \Lambda \sim 2M_H \end{cases}$$

Experimental bound (LEP 2), $e^+e^- \rightarrow Z^* \rightarrow ZH \Rightarrow M_H \gtrsim 114.5$ GeV at 95% cl

Hint of signal at 115 GeV

Indirect (precision tests): $M_H < 215$ GeV, 95% cl

MSSM: much of parameter space has standard-like Higgs with $M_H < 130$ GeV



Theoretical M_H limits, Hambye and Riesselmann, hep-ph/9708416

Decays: $H \rightarrow \bar{b}b$ dominates for $M_H \lesssim 2M_W$ ($H \rightarrow W^+W^-$, ZZ dominate when allowed because of larger gauge coupling)

Production:

LEP: Higgstrahlung ($e^+e^- \rightarrow Z^* \rightarrow ZH$)

Tevatron, LHC: $GG \rightarrow H$ via top loop), WW fusion ($WW \rightarrow H$), or associated production ($\bar{q}q \rightarrow WH$, ZH)

First term in V : vacuum energy

$$\langle 0|V|0\rangle = -\mu^4/4\lambda$$

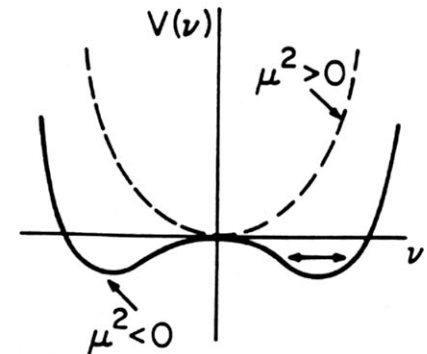
No effect on microscopic interactions, but gives *negative* contribution to cosmological constant

$$|\Lambda_{\text{SSB}}| = 8\pi G_N |\langle 0|V|0\rangle| \sim 10^{50} |\Lambda_{\text{obs}}|$$

Require fine-tuned cancellation

$$\Lambda_{\text{cosm}} = \Lambda_{\text{bare}} + \Lambda_{\text{SSB}}$$

Also, QCD contribution from SSB of global chiral symmetry



Yukawa Interactions

$$\begin{aligned} -\mathcal{L}_{\text{Yukawa}} &\rightarrow \sum_{m,n=1}^F \bar{u}_{mL}^0 \Gamma_{mn}^u \left(\frac{\nu + H}{\sqrt{2}} \right) u_{mR}^0 + (d, e) \text{ terms} + \text{H.C.} \\ &= \bar{u}_L^0 (M^u + h^u H) u_R^0 + (d, e) \text{ terms} + \text{H.C.} \end{aligned}$$

$u_L^0 = (u_{1L}^0 u_{2L}^0 \cdots u_{FL}^0)^T$ is F -component column vector

M^u is $F \times F$ fermion mass matrix $M_{mn}^u = \Gamma_{mn}^u \nu / \sqrt{2}$ (need not be Hermitian, diagonal, symmetric, or even square)

$h^u = M^u / \nu = g M^u / 2M_W$ is the Yukawa coupling matrix

Diagonalize M by separate unitary transformations A_L and A_R
 (($A_L = A_R$) for Hermitian M)

$$A_L^{u\dagger} M^u A_R^u = M_D^u = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix}$$

is diagonal matrix of physical masses of the charge $\frac{2}{3}$ quarks.
 Similarly

$$\begin{aligned} A_L^{d\dagger} M^d A_R^d &= M_D^d \\ A_L^{e\dagger} M^e A_R^e &= M_D^e \\ (A_L^{e\nu\dagger} M^\nu A_R^\nu &= M_D^\nu) \end{aligned}$$

(may also be Majorana masses for ν_R)

Find A_L and A_R by diagonalizing Hermitian matrices MM^\dagger and $M^\dagger M$, e.g., $A_L^\dagger MM^\dagger A_L = M_D^2$

Mass eigenstate fields

$$u_L = A_L^{u\dagger} u_L^0 = (u_L \ c_L \ t_L)^T$$

$$u_R = A_R^{u\dagger} u_R^0 = (u_R \ c_R \ t_R)^T$$

$$d_{L,R} = A_{L,R}^{d\dagger} d_{L,R}^0 = (d_{L,R} \ s_{L,R} \ b_{L,R})^T$$

$$e_{L,R} = A_{L,R}^{e\dagger} e_{L,R}^0 = (e_{L,R} \ \mu_{L,R} \ \tau_{L,R})^T$$

$$\nu_{L,R} = A_{L,R}^{\nu\dagger} \nu_{L,R}^0 = (\nu_{1L,R} \ \nu_{2L,R} \ \nu_{3L,R})^T$$

(For $m_\nu = 0$ or negligible, define $\nu_L = A_L^{e\dagger} \nu_L^0$, so that $\nu_i \equiv \nu_e, \nu_\mu, \nu_\tau$ are the weak interaction partners of the $e, \mu,$ and τ .)

Typical estimates: $m_u = 5.6 \pm 1.1 \text{ MeV}$, $m_d = 9.9 \pm 1.1 \text{ MeV}$, $m_s = 199 \pm 33 \text{ MeV}$, $m_c = 1.35 \pm 0.05 \text{ GeV}$, $m_b \sim 4.7 \text{ GeV}$, $m_t = 174.3 \pm 5.1 \text{ GeV}$

Implications for global $SU(3)_L \times SU(3)_R$ of QCD

These are current quark masses. $M_i = m_i + M_{dyn}$, $M_{dyn} \sim \Lambda_{\overline{MS}} \sim 300 \text{ MeV}$ from chiral condensate $\langle 0 | \bar{q}q | 0 \rangle \neq 0$

$m_{b,t}$ are pole masses; others, running masses at 1 GeV^2

Yukawa couplings of Higgs to fermions

$$L_{\text{Yukawa}} = \sum_i \bar{\psi}_i \left(-m_i - \frac{gm_i}{2M_W} H \right) \psi_i$$

Coupling $gm_i/2M_W$ is flavor diagonal and small except t quark

$H \rightarrow \bar{b}b$ dominates for $M_H \lesssim 2M_W$ ($H \rightarrow W^+W^-$, ZZ dominate when allowed because of larger gauge coupling)

Flavor diagonal because only one doublet couples to fermions \Rightarrow fermion mass and Yukawa matrices proportional

Often flavor changing Higgs couplings in extended models with two doublets coupling to same kind of fermion (*not* MSSM)

Stringent limits, e.g., tree-level Higgs contribution to $K_L - K_S$ mixing (loop in standard model) $\Rightarrow h_{\bar{d}s}/M_H < 10^{-6} \text{GeV}^{-1}$