Electroweak physics and the LHC
an introduction to the Standard Model

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Outline

- Prologue on weak interactions
- Express review of gauge theories
- SM gauge sector
- Hidden symmetries
- SM Higgs sector
- Precision tests of the SM
- anomalous magnetic moments
- Computing G_F
- Global fit and the Higgs mass
- Electroweak physics at LHC

A few references

books:

- Peskin & Schoeder, *Quantum Field Theory*
- Donoghue,Golowich,Holstein, *Dynamics of the SM*
- Cheng & Li, *Gauge theory of elementary particle physics*
- Becchi & Ridolfi, *Introduction to relativistic processes and the SM*

lectures sets:

- Altarelli, *hep-ph/0011078*
- Ridolfi, see http://www.ge.infn.it/~ridolfi/

Prologue

Weak forces are *weak*

$$\mathcal{L} = -\frac{G^{(\beta)}}{\sqrt{2}}\overline{p}\gamma^\alpha(1-a\gamma_5)n\,\overline{e}\gamma_\alpha(1-\gamma_5)\nu_e - \frac{G^{(\mu)}}{\sqrt{2}}\overline{\nu}_\mu\gamma^\alpha(1-\gamma_5)\mu\,\overline{e}\gamma_\alpha(1-\gamma_5)\nu_e$$

Fermi Lagrangian describes beta (semileptonic) decays $a=1.269\pm0.003$

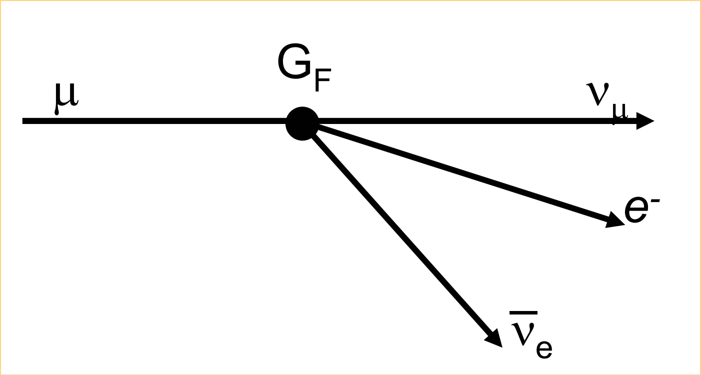
$$\mathcal{L} = -\sum_i \frac{G_F^{(i)}}{\sqrt{2}} J_i^\mu J_\mu^e$$

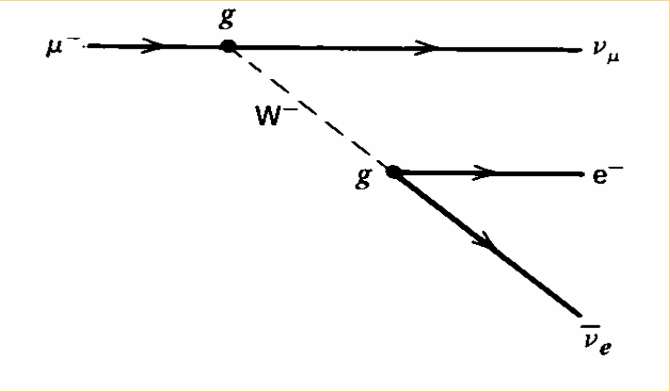
$G^{(\mu)} \simeq 1.16639 \times 10^{-5}\ \mathrm{GeV}^{-2}$; $G^{(\beta)} \simeq G^{(\mu)} = G_F$

typical process $\sim G_F E^2$; *n decay* $G_F m_p^2 \sim 10^{-5} \ll \alpha = 1/137$

- growth with energy incompatible with unitarity: only valid up to $\Lambda\sim$100GeV
- non-renormalizable: gives good predictions, but they cannot be consistently improved
- short range interaction $r_W \sim 1\times10^{-3}$ fm
- vector currents: Intermediate Vector Boson hypothesis

Intermediate Vector Boson





$$\frac{g^2}{p^2 - M_W^2} \approx -\frac{g^2}{M_W^2} \propto -G_F$$

Further lessons from $\mathcal{L}^{\text{Fermi}}$

$$\mathcal{L} = -\frac{G^{(\beta)}}{\sqrt{2}}\overline{p}\gamma^\alpha(1-a\gamma_5)n\,\overline{e}\gamma_\alpha(1-\gamma_5)\nu_e - \frac{G^{(\mu)}}{\sqrt{2}}\overline{\nu}_\mu\gamma^\alpha(1-\gamma_5)\mu\,\overline{e}\gamma_\alpha(1-\gamma_5)\nu_e$$

$G^{(\mu)} \simeq 1.16639 \times 10^{-5}\ GeV^{-2}$;

Improved fundamental theory should moreover include:

- **chiral** structure, P and C violation
- **universality** of weak coupling $G^{(\beta)} \simeq G^{(\mu)} = G_F$
- **flavor** violation (K_{l3}) but no flavor changing neutral currents (FCNC)
- common vector interactions hint at possible **electroweak unification** (Schwinger 1957, Glashow...)

All these points have a natural solution in the framework of **Gauge theories**

Express review of gauge theories

Continuous symmetries

- **Classical Mechanics**: invariance of a system under cont. transf.
  → constants of motion $E, \vec{p}, \vec{J} \ldots$
- **Quantum Mechanics**: O_i conserved if $[O_i,H]=0$, O_i generator of unitary tranf. that leaves system unchanged

- **Field Theory** T: $\phi_i(x) \to U_{ij}\phi_j(x)$ leaves EOM or $\mathcal{S}=\int d^4x\, \mathcal{L}$ unchanged:
  it is a *symmetry.*

Noether Theorem: the current $j^\mu(x) = \frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi)}\delta\phi$
is conserved: $\partial_\mu j^\mu(x)=0$.

$\mathcal{Q}=\int d^3x\, j_0(x)$ is constant and generates the transformation

At the quantum level the symmetry generates Ward identities between Green's functions

Noether currents ←→ physical weak currents
?

Examples of global symmetries

- $\mathcal{L} = \partial_\mu\phi^* \partial^\mu\phi - \mu^2|\phi|^2 - \lambda\, |\phi|^4$

  $\phi\,(x) \rightarrow e^{i\,\alpha}\,\phi\,(x)$ change of phase

  charge current $j_\mu = i\,[\partial_\mu\phi^*\,\phi - \phi^*\,\partial_\mu\phi]$ is conserved

- $\mathcal{L} = \partial_\mu\phi^\dagger\partial^\mu\phi - \mu^2\phi^\dagger\phi - \lambda/2\,(\phi^\dagger\phi)^2$ $\quad \phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$

  SU(2) invariant under $\phi \rightarrow \phi + ½\, i\varepsilon_i\, \tau_i\, \phi$ $\quad \tau_i$ *Pauli matrices*

  3 conserved currents, 3 charges satisfy Lie algebra $[Q_a, Q_b] = i\, \varepsilon_{abc}\, Q_c$

- $\mathcal{L} = \bar{N}(i\partial\!\!\!/ - M)N + \frac{1}{2}[\partial_\mu\vec{\pi}\partial^\mu\vec{\pi} - m_\pi^2\vec{\pi}^2] + ig\bar{N}\vec{\tau}\cdot\vec{\pi}\gamma_5 N - \frac{\lambda}{4}\vec{\pi}^4$

  with $N = \begin{pmatrix} p \\ n \end{pmatrix}$, $\vec{\pi} = \pi_i$ $i = 1,2,3$ $\quad m_\pi \approx 140\text{MeV},\ M \approx 940\text{MeV}$

  is SU(2) invariant wrt $N \rightarrow e^{-i\frac{\vec{\tau}}{2}\cdot\vec{\pi}}N = UN$ and $\vec{\tau}\cdot\vec{\pi} \rightarrow U\vec{\tau}\cdot\vec{\pi}U^\dagger$

  Degenerate multiplets, universal couplings, conserved currents

  $V_\mu^i = \bar{N}\gamma_\mu\frac{\tau_i}{2}N + \epsilon^{ijk}\pi^j\partial_\mu\pi^k \simeq J_\mu^W + \ldots$ CVC hypothesis $\rightarrow \pi\ell_3$ decay

Gauge theories: local abelian symmetry

Dirac free $\mathcal{L}= \bar\psi(i \partial\!\!\!/ - m)\, \psi$ invariant under

$$\psi \to e^{i e \alpha}\, \psi, \quad \bar\psi \to e^{-i e \alpha}\, \bar\psi$$

If $\alpha=\alpha(x)$ *local invariance* requires

$$\partial^\mu \to D^\mu \equiv \partial^\mu - i\, e\, A^\mu,$$ covariant derivative *[minimal coupling]*

$$A^\mu \to A^\mu + \partial^\mu \alpha(x),$$ A^μ real vector field *[E&M gauge invariance]*

$$\mathcal{L}^{QED} = \bar\psi\, (i\, D\!\!\!\!/ - m)\, \psi - \tfrac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$= \bar\psi\, (i\, \partial\!\!\!/ - m)\, \psi + e A^\mu J_\mu - \tfrac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

with $F^{\mu\nu}\psi = i/e\, [D^\mu, D^\nu]\, \psi$ *gauge invariant*

No photon gauge invariant mass term. Ward identities $k_\mu M^\mu(k)=0$

Non-abelian local symmetry

SU(N): N^2-1 generators t^a in representation R,

$[t^a,t^b]=i f^{abc} t^c$; f^{abc} antisymmetric

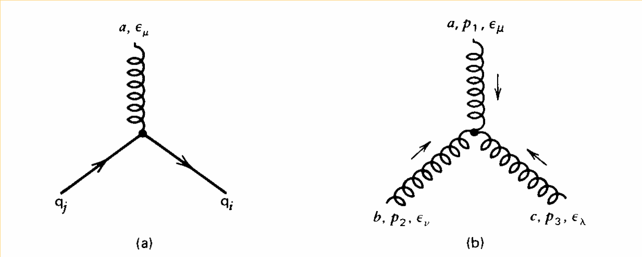
Generic element $U=e^{ig\alpha^a t^a}$ identifies a gauge t. of ψ Yang-Mills (1954)

Covariant derivative $D^\mu=\mathbf{1}\partial^\mu - i g A^\mu_a t^a$, $D^\mu \to U D^\mu U^{-1}$ (D^μ transf. like ψ)

$$F_a^{\mu\nu} t^a \psi = i/g\, [D^\mu, D^\nu]\psi$$

$$F_a^{\mu\nu} = \partial^\mu A_a^\nu - \partial^\nu A^\mu_a + g f^{abc} A^\mu_b A^\nu_c$$

kinetic term $-\frac{1}{4} F_a^{\mu\nu} F^a_{\mu\nu}$ is gauge invariant, unlike $F_a^{\mu\nu}$



Gauge field self-interaction imposed by gauge invariance. Yang-Mills theories are non-trivial even without matter fields. Gauge fields carry charge: cons. currents include a pure gauge term

Gauge theories: symmetry dictates dynamics

- By promoting global to local **symmetry** *[local gauge principle]* gauge theories allow for vector bosons
- **Symmetry** makes some d.o.f. redundant: $A^0, \nabla\cdot\mathbf{A}$ are *c-numbers.* Gauge fixing necessary to quantize theory.
- **Symmetry** dictates form of allowed interactions. Gauge fields self-interact, hence single universal coupling for each group $-g\, J_\mu^a\, A^\mu_a$
- **Symmetry** permits the renormalization of gauge theory
- **Symmetry** forbids mass terms for the vector bosons. QCD, based on SU(3) is the most beautiful realization *[asymptotic freedom]*

The gauge sector of the SM

Which gauge symmetry?

We assume that currents in $\mathcal{L}^{\text{Fermi}}$ are Noether currents

$$J^{\ell}_{\mu} = \bar{\nu}\gamma_{\mu}\tfrac{1}{2}(1-\gamma_5)e = \bar{\nu}_L\gamma_{\mu}e_L$$

Let's group e_L, ν_L in a doublet $L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$

$$\tau^{+} = \tfrac{1}{2}(\tau_1 + i\tau_2) = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \quad J_{\mu} = \bar{L}\gamma_{\mu}\tau^{+}L, \qquad J^{\dagger}_{\mu} = \bar{L}\gamma_{\mu}\tau^{-}L$$

$$J^3_{\mu} = \bar{L}\gamma_{\mu}\tau^3 L = \bar{\nu}_L\gamma_{\mu}\nu_L - \bar{e}_L\gamma_{\mu}e_L$$

SU(2) group in fundamental representation, simplest choice ν_R, e_R singlets
Neutral current $J_{\mu}^{3} \neq J_{\mu}^{\gamma}$ (because of chirality & neutrinos) what is it?

Now promote SU(2) to local symmetry: $D^{\mu} = \partial^{\mu} - i\, g\, W_i^{\mu}\, T_i$; $W^{\pm}_{\mu} = (W^1_{\mu} \mp i\, W^2_{\mu})/\sqrt{2}$

$$\mathcal{L} = i\bar{L}\not{D}L + i\bar{\nu}_R\not{\partial}\nu_R + i\bar{e}_R\not{\partial}e_R = \text{kin.} + \frac{g}{\sqrt{2}}J_{\mu}W^{\mu} + \text{h.c.} + \frac{g}{2}J^3_{\mu}W^{\mu}_3$$

Explains G_F in terms of gauge couplings $G_F = \sqrt{2}\, g^2/8M_W^2$

Neutral currents: electroweak unification

One way to solve the NC problem is to extend the gauge group SU(2)→SU(2)xU(1). Extra abelian ***hypercharge*** Y differs for L,R fields. $D^\mu = \partial^\mu - i\, g\, W_i^\mu\, T_i - \frac{1}{2}\, i\, g'\, Y\, B^\mu$

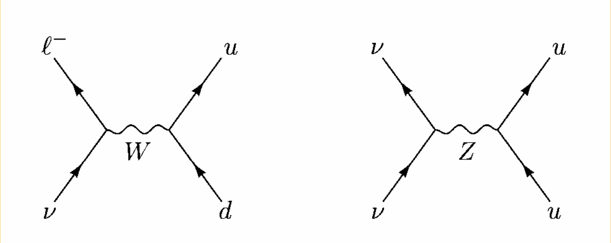
$$\mathcal{L}^{NC} = \Sigma_\psi \left[g\bar\psi\gamma_\mu T_3 \psi W_3^\mu + g'\bar\psi\gamma_\mu \tfrac{Y}{2}\psi B^\mu \right] \qquad T_3 = \pm\tfrac{1}{2}, 0$$

$$B^\mu = A^\mu \cos\theta_W - Z^\mu \sin\theta_W; \qquad W_3^\mu = A^\mu \sin\theta_W + Z^\mu \cos\theta_W$$

In order to have J_μ^γ coupled to A^μ : $T_3\, g \sin\theta_W + \frac{1}{2} Y\, g' \cos\theta_W = eQ$
The choice Y(L)=-1 $Y(e_R)=-2$ $Y(\nu_R)=0$ implies **$g \sin\theta_W = g' \cos\theta_W = e$**

The Z neutral current has charge $Q_Z = (T_3 - Q\, s^2_W)/c_W\, s_W$, $s_W = \sin\theta_W$

A definite prediction: weak NCs have been first observed in 1973!



Hadronic currents

Using QUARK L doublets and R singlets, it's like for leptons **but** flavor change has long been observed in charged currents (CC).

On the other hand, FCNCs strongly suppressed (higher order effects):

$$\text{ex.:} \quad \frac{\Gamma(K^+ \to \pi^+ e^+ e^-)}{\Gamma(K^+ \to \pi^0 e^+ \nu)} \simeq \left| \frac{\bar{s} \to \bar{d} e^+ e^-}{\bar{s} \to \bar{u} e^+ \nu} \right|^2 \approx 10^{-5}$$

Solution (Glashow, Iliopoulos, Maiani 1970): quark doublets

$$Q = \begin{pmatrix} u_L \\ d'_L \end{pmatrix}, \begin{pmatrix} c_L \\ s'_L \end{pmatrix}, \begin{pmatrix} t_L \\ b'_L \end{pmatrix} \text{where} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

in this way NC conserve flavor (at lowest perturbative order):

$$J_3^\mu \propto \bar{d}'_L \gamma^\mu d'_L = \bar{d}_L \gamma^\mu V^\dagger_{CKM} V_{CKM} d_L = \bar{d}_L \gamma^\mu d_L$$

The CKM matrix → Ciuchini's lectures

describes Flavor Violation (mixing between generations of quarks) in the SM

$$\mathcal{L}_W = -\frac{g}{2\sqrt{2}} V_{ij} \bar{u}_{i,L} \gamma^\mu W^+_\mu d_{j,L} + \text{h.c.}$$

Wolfenstein parameterization

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.9740 \pm 0.0010 & 0.2196 \pm 0.0023 & 0.0040^{+0.0006}_{-0.0007} \\ 0.224 \pm 0.016 & 0.91 \pm 0.16 & 0.0402 \pm 0.0019 \\ < 0.010 & \simeq 0.0400 & 0.99 \pm 0.29 \end{pmatrix}$$

3 angles and 1 phase with strong hierarchy:
$\lambda \sim 0.22$ sine of Cabibbo angle, $A, \rho, \eta = O(1)$

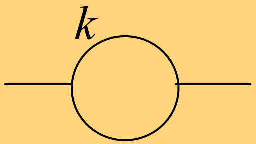
The CKM phase is the only source of CP violation in the SM

Summary of matter fields

	SU(2)	U(1) (Y)	$SU(3)_{QCD}$
L	2	-1	1
e_R	1	-2	1
Q	2	1/3	3
u_R	1	4/3	3
d_R	1	2/3	3
ν_R	1	0	1

NB SU(2)xU(1) is semisimple: Y is arbitrary → no charge quantization in SM

Renormalizability

- Loops integrations 

generally divergent in the UV

$$\int d^4k \frac{1}{(k^2-m^2)^2} \propto \ln \frac{\Lambda^2}{m^2} + \ldots \quad \Lambda \text{ cutoff}$$

- A theory is **renormalizable** if all divergences can be reabsorbed at each pert. order in a redefinition of the parameters of $\mathcal{L}$.
- systematics of renormalization: dim $\leq$ 4 terms in $\mathcal{L}$ are *generally* renormalizable. Cutoff dependence is **power-suppressed**.
- Yang-Mills gauge theories are renormalizable, like QED
- Renormalizability **guiding principle** in SM evolution: weak coupling renormalizable th. are predictive, have small pert. corrections
- Massive vector bosons: $\mathcal{L}=-\frac{1}{4}(\partial^\mu W^\nu-\partial^\nu W^\mu)(\partial_\mu W_\nu-\partial_\nu W_\mu)+M_W^2\, W_\mu W^\mu/2$

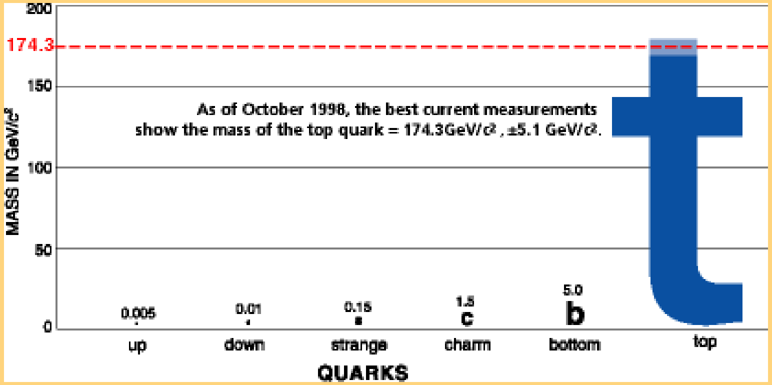
$$\Delta^{\mu\nu} = \frac{i}{k^2-M_W^2}\left(-g^{\mu\nu}+\frac{k^\mu k^\nu}{M_W^2}\right) \rightarrow \text{const for } k \rightarrow \infty$$

A massive problem

Also fermion masses break SU(2) symmetry:

$$m_e \bar{e} e = m_e [\bar{e}_L e_R + \bar{e}_R e_L]$$

because e_R and e_L belong to different multiplets.



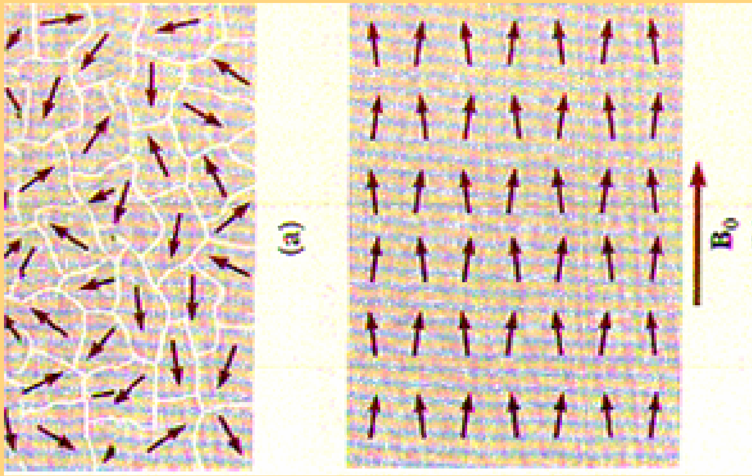
Exp: Currents are conserved to high accuracy!
SU(2)xU(1) works beautifully

BUT HOW DO WE GET THE MASSES?

On the fate of symmetries

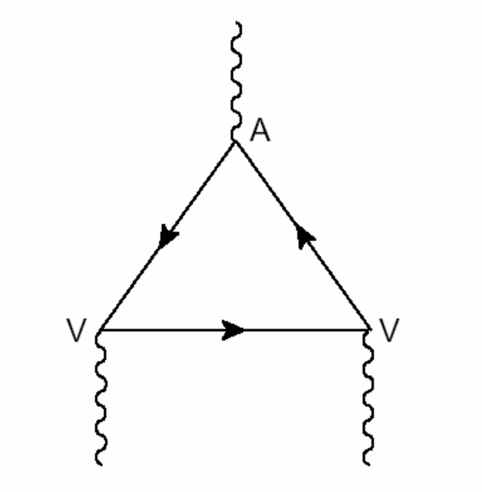
- Symmetries can be **exact**: $U(1)_{em}$, $SU(3)_{QCD}$, B-L
- Or they can be **explicitly broken** by (small) terms: SU(2) isospin is broken by $m_{u,d}$ and by QED Still useful.
- They can broken by quantum corrections, have **anomalies**: eg scale invariance in massless QFT is anomalous, a new scale appears.
- They can be **Spontaneously broken**: the ground state is NOT symmetric, although the interactions respect the symmetry. Two possibilities: a scalar field acquires a vev, or dynamical breaking (chiral $SU(2)_R x SU(2)_L$ of strong int)

It is quite common in nature that the lowest energy state is not symmetric: ex **ferromagnet** below the Curie temperature



A miracolous cancellation

Axial anomaly: impossible to regularize a field th in a way that preserves both axial and vector conservation Ward id. (gauge invariance) spoiled by loops (triangle)



$J_A^\mu = \psi\, \gamma^\mu\, \gamma^5\, \psi$; $\quad \partial_\mu J_A^\mu = \varepsilon_{\mu\nu\rho\sigma} F^{\mu\nu} F^{\rho\sigma}/4\pi^2$ +mass terms

Non-abelian case: **anomaly $\propto$ Tr($\{T^a,T^b\}T^c$)** $\quad T^i=\tau^i$,Y

SU(2) not anomalous, yet

ex $\mathrm{Tr}(\{\tau^a,\tau^b\}Y) = 2\delta^{ab}\, \mathrm{Tr}\, Y_L =$

$2\delta^{ab}\, [n_q x3x2x1/3 + n_l x2x(-1)] \propto n_q - n_l$

and similarly for all other gauge currents of SM. **Why? hint of GUTs?**

SM has also ***accidental*** global symmetries, rephasing invariance that is a consequence of the assumed gauge symmetry and renormalizability: B, L_e,L_μ,L_τ .
B and L are anomalous, B-L is not. $B(\mu\to 3e)<10^{-12}$ but cosmological consequences

Hidden symmetry

we need a mechanism of Spontaneous Symmetry Breaking (SSB)

$$m\neq 0 \iff \langle 0|X|0\rangle \neq 0 \quad \text{(v.e.v.)}$$

X could be a scalar field or condensate, should be SU(2) doublet, vev~250GeV
Langrangian symmetric, currents conserved, spectrum and vacuum not invariant.

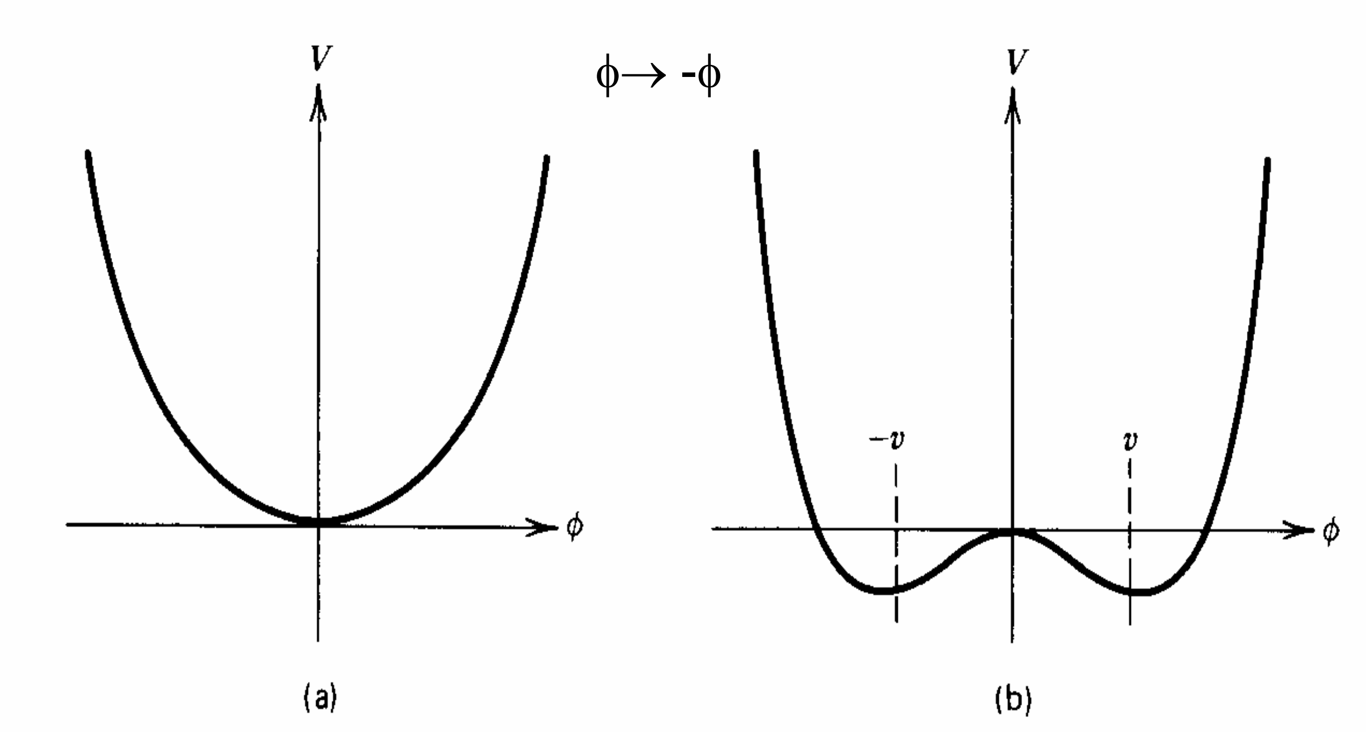
Goldstone theorem: as many massless bosons as the broken continuous symmetries: if $Q_i\,|0\rangle \neq 0$ but $[H,Q_i]=0$, $Q_i|0\rangle$ is degenerate with $|0\rangle$.
Goldstone th is EVADED in gauge theories due to longitudinal vector bosons.

SSB does not spoil renormalizability (soft breaking)

The **Higgs mechanism** realizes SSB in SM in the most economical way: X is single complex doublet of fundamental scalars, predicting the existence of a new particle, the **HIGGS BOSON**.

At the same time massive vector bosons are quantized without spoiling renormalizability and unitarity.

Hidden (discrete) symmetry



$\mathcal{L} = ½ (\partial_\mu \phi)^2 - ½\ m^2 \phi^2 - ¼ \lambda \phi^4 \rightarrow \mathcal{L} = ½ (\partial_\mu \phi)^2 + ½ \mu^2 \phi^2 - ¼ \lambda \phi^4$

Potential minimized by $\phi=0 \rightarrow \phi=\pm \mu/\lambda^{½} = v$ **$\langle 0|\phi|0\rangle = v$**

excitations around vacuum: $\phi = v + \phi'$ symmetry is no longer manifest

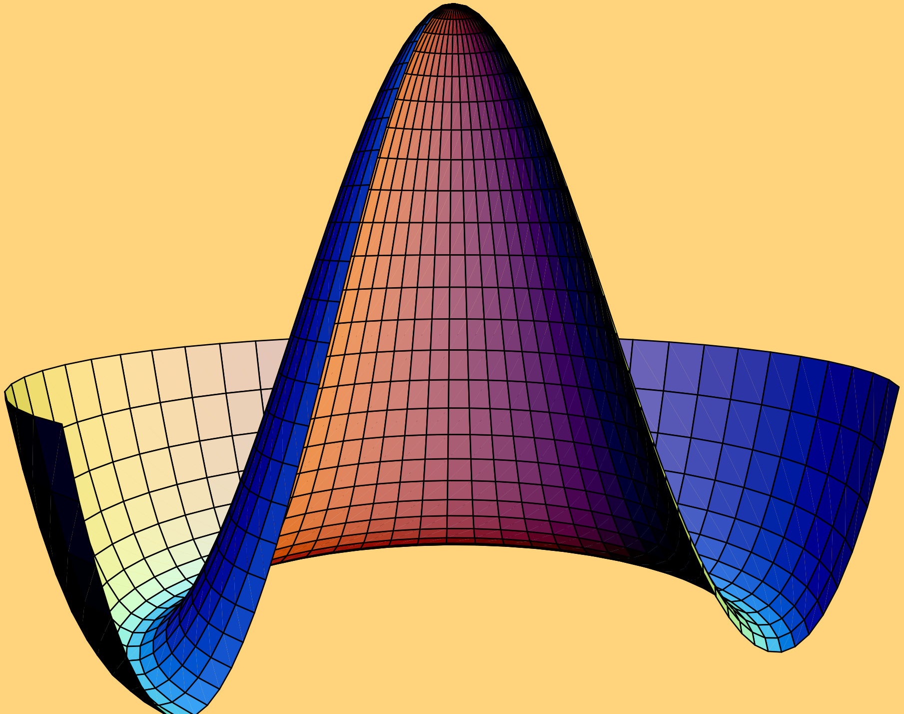
$\mathcal{L} = ½ (\partial_\mu \phi')^2 - m^2 \phi'^2 - \lambda v \phi'^3 - ¼ \lambda \phi'^4$

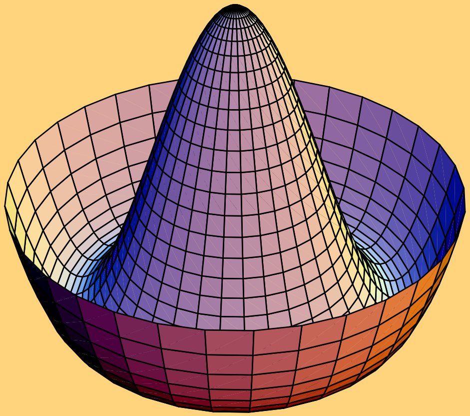
Abelian Higgs mechanism

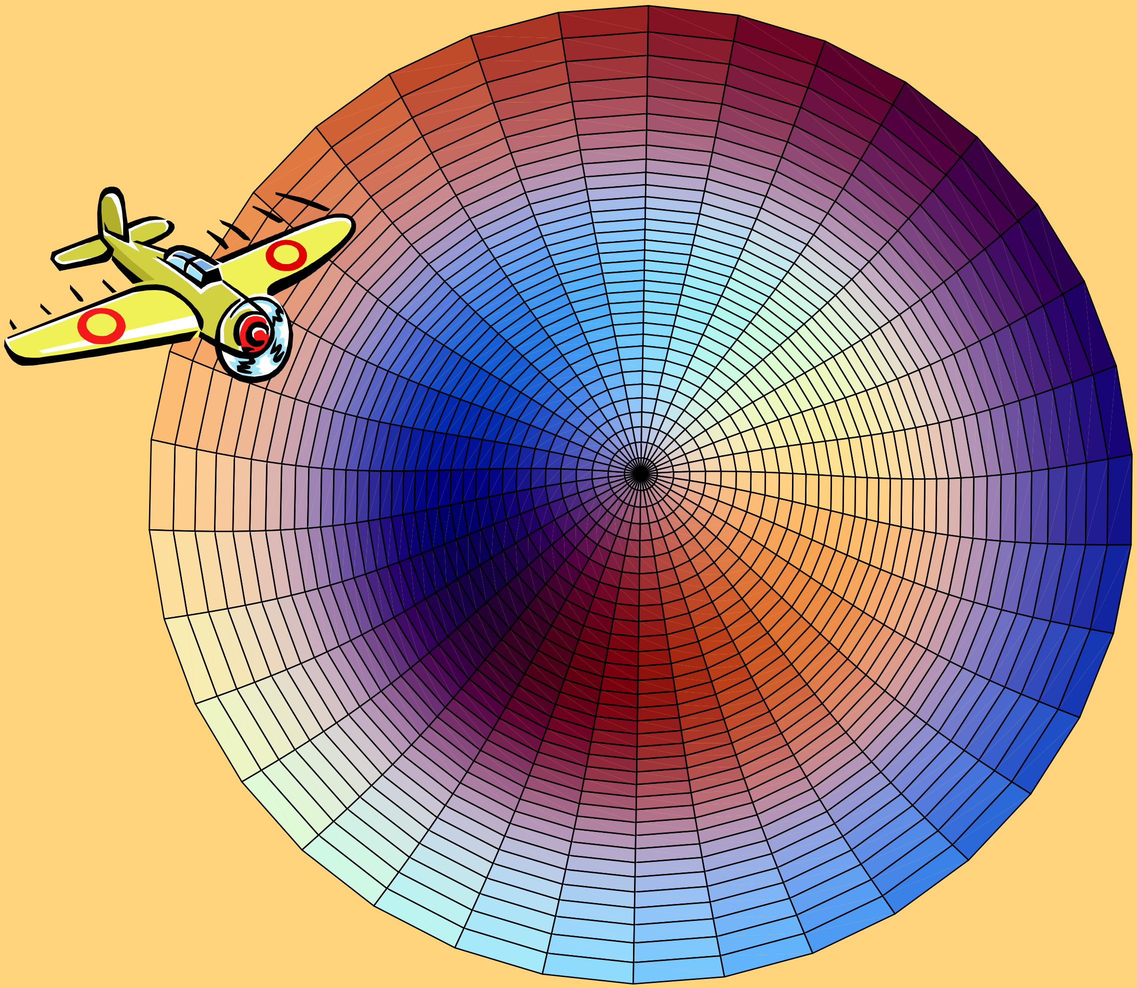
$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}F^{\mu\nu} + (D^{\mu}\phi)^{\dagger} D_{\mu}\phi - V(\phi)$ U(1) invariant

with $D_{\mu} = \partial_{\mu} - i\, e\, A_{\mu}$ *and* $V(\phi) = m^2|\phi|^2 + \lambda\, |\phi|^4$ (most general renorm.)

If $m^2<0$, $\lambda>0$, we have an infinite number of degenerate vacua for $|\phi|^2 = -m^2/2\lambda \equiv \frac{1}{2} v^2$ connected by gauge transf.







Symmetry becomes apparent only at high energies

Abelian Higgs mechanism (II)

Decompose *$\phi(x) = [v+H(x)+i\,G(x)]/\sqrt{2}$*   *H,G real*

In *L* the terms $\propto$ H, G^2 vanish ie G is a Goldstone boson.

$(D_\mu \phi)^\dagger D^\mu \phi = \frac{1}{2} e^2 v^2 A_\mu A^\mu + \ldots$ **VB has acquired a mass M = e v**

After proper gauge fixing $-(\partial^\mu A_\mu + e\,v\,\xi\,G)^2/2\xi$

the A propagator becomes

$$\Delta^{\mu\nu} = \frac{i}{k^2 - M_A^2}\left[-g^{\mu\nu} + \frac{(1-\xi)k^\mu k^\nu}{k^2 - M_A^2\xi}\right]$$

good UV behaviour. In the limit $\xi \to \infty$ (unitary gauge)

the Goldstone boson decouples and one recovers the usual propagator

The number of dof is constant: we had a complex ϕ, now we have H and the longitudinal polarization of A

Higgs mechanism in the SM

we want <0|ϕ|0>=v$\neq$ 0 ϕ in red. repr. of SU(2)xU(1) but must preserve $U(1)_{em}$: SSB concerns 3 generators

$V(\phi)= m^2 |\phi|^2 +\lambda |\phi|^4$ minimized by $|\phi_0|^2= -m^2/2\lambda \equiv v^2/2$

Simplest solution: ϕ doublet ➔ $U(1)_{em}$ inv. imposes Y=1

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

$$V(H) = \frac{1}{2}(2\lambda v^2)H^2 + \lambda v H^3 + \frac{\lambda}{4}H^4 \qquad M_H = \sqrt{2\lambda} v$$

from covariant derivatives

$$M_W^2 = \frac{1}{4}g^2v^2 \quad M_Z^2 = \frac{1}{4}(g^2+g'^2)v^2 \quad m_\gamma = 0$$

$$v = \sqrt{1 G_F \sqrt{2}} \simeq 246\,\mathrm{GeV}$$

natural relation $\rho_0 = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = \frac{g^2}{(g^2+g'^2)\cos^2\theta_W} = 1$

with more ϕ doublets, triplets... $\rho_0 = \frac{\sum_i [(t_i)^2 + t_i - (t_i^3)^2] v_i^2}{\sum_i 2(t_i^3)^2 v_i^2} \neq 1$

Yukawa couplings

ϕ can couple to matter fields as well. Most general gauge inv and renorm form

$$\mathcal{L}_Y^{hadr} = -\bar{Q}'\phi h'_d d'_R - \bar{d}'_R \phi^\dagger h'^\dagger_d Q' - \bar{Q}'\phi_c h'_u u'_R - \bar{u}'_R \phi^\dagger_c h'^\dagger_u Q'$$

where $\phi_c = \epsilon\phi^* = \begin{pmatrix} \phi^0 \\ -\phi^- \end{pmatrix}$

The Yukawa matrices are diagonalized by biunitary transf

$$h_{u,d} \equiv V_L^{u,d\dagger} h'_{u,d} V_R^{u,d}$$

$$u'_{L,R} = V^u_{L,R} u_{L,R} \qquad d'_{L,R} = V^d_{L,R} d_{L,R}$$

Unitary gauge: $\mathcal{L}_Y^{hadr} = -\frac{1}{\sqrt{2}}(v+H)\sum_f (h_d^f \bar{d}^f d^f + h_u^f \bar{u}^f u^f)$

SM accomodates flavor: there is no theory of flavor!

masses $\propto$ Yukawas only for 1 doublet

Leptons (no ν mass): same but no LFV, BR($\mu \to e\gamma$)<10^{-11}