The Standard Model and beyond (3)
Electroweak unification

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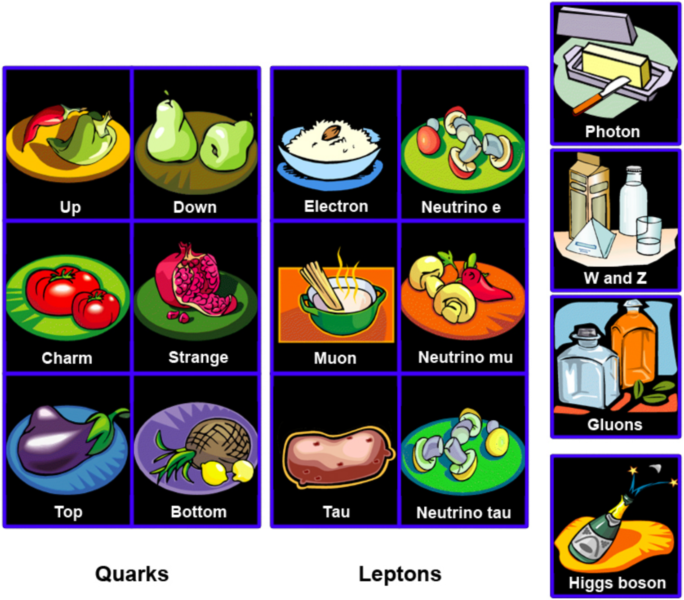


Quarks **Leptons**

Fermions **Bosons**

Second lecture

Symmetries

- Abelian (2D rotations) or nonabelian (3D rotations) groups
- Infinitesimal rotations given by generators obeying a Lie algebra
- Objects transform under given representations
- Flavour symmetries as illustration of global symmetries

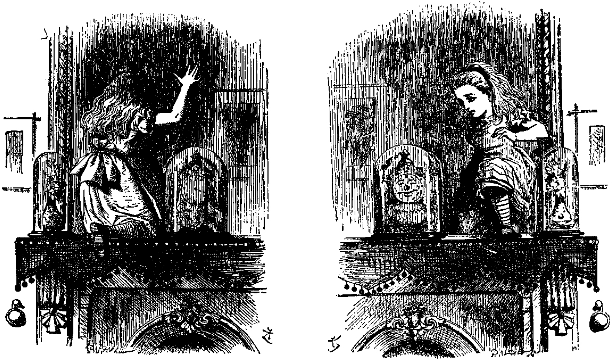
Quantum Chromodynamics

- Coloured quarks, interacting through strong interaction
- Gauge principle: invar under local $SU(3)$ rotations in colour space
- New fields G^a_μ corresponding to 8 gluons coupling to quarks (like in QED) but also to other gluons (nonabelian group)
- Variation with distance: asymptotic freedom, confinement
- Tests in deep inelastic scattering, lattice QCD, jets at LHC

Parity and charge conjugation

Parity

Parity: $\vec{r} \to -\vec{r}$

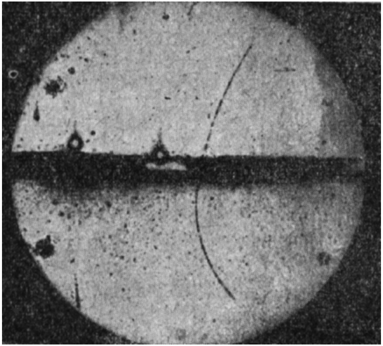


the mirror-world (or rather 3-mirror world)

Charge conjugation

Antiparticles exist (Dirac (1929) & Anderson (1932))

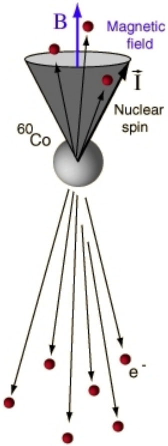
- same mass, opposite quantum numbers
- annihilation/creation of particle-antiparticle



$\Longrightarrow$Associated symetries: C and P

Discrete symmetries with $C^2 = 1$, $P^2 = 1$

Weak forces, C and P



1956, Mrs Wu
β decay of cobalt $^{60}Co \to {}^{60}Ni + e^- + \bar{\nu}_e$
emits e^- rather opposite to spin

P inverts e^- direction but not spin
$\Longrightarrow$if P conserved, isotropic emission !

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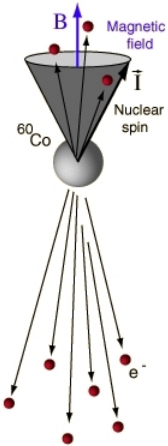

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Further investigations:
Weak decays respect neither P nor C
(and what about CP ?)

Chirality and helicity

- Helicity: Projection of spin on direction of motion (frame-depend)

$$h = \frac{\vec{S} \cdot \vec{p}}{|\vec{p}|}$$

Spin-1/2 particle (electron) [opposite for antifermion]:

$h = 1/2$ right-handed, $h = -1/2$ left-handed

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$$P_R = \frac{1+\gamma_5}{2}, \quad P_L = \frac{1-\gamma_5}{2}, \quad \Psi = (P_L + P_R)\Psi = \Psi_L + \Psi_R$$

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$$\begin{aligned} \mathcal{L} &= \bar\psi(i\gamma^\mu\partial_\mu - m)\psi & \bar\psi = \psi^\dagger\gamma^0 \\ &= \bar\psi_L i\gamma^\mu\partial_\mu\psi_L + \bar\psi_R i\gamma^\mu\partial_\mu\psi_R - m(\bar\psi_L\psi_R + \bar\psi_R\psi_L) \end{aligned}$$

C, *P* and *CP* act on chiral fermions

$$\begin{array}{ccccc} \psi_L & \leftarrow & C & \rightarrow & \bar\psi_L \\ \uparrow & & & & \uparrow \\ P & & & & P \\ \downarrow & & & & \downarrow \\ \psi_R & \leftarrow & C & \rightarrow & \bar\psi_R \end{array}$$

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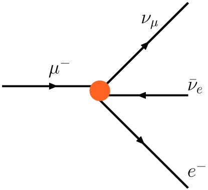
- A theory with a different treatment of $L \neq R$ (chiral theory) violates *P* and *C*, but not necessarily *CP*
- Sakharov conditions for baryogenesis, i.e. matter-antimatter asymmetry from Big Bang
  - Reactions with violation of baryon number
  - Reactions with *C* and *CP* violation
  - Interactions out of thermal equilibrium

Weak interactions

A few observations

Charged weak currents
(charged boson exchange ?)



- Only left-handed fermions produced (right-handed antifermions)
- Doublet partners (ℓ, ν_ℓ): $\nu_\mu X \to \mu^- X'$ but not $\nu_\mu X \to e^- X'$
- Universal strength: $\Gamma(\ell \to \nu_\ell \ell' \bar{\nu}_{\ell'}) \sim G_F^2 m_\ell^5$

Neutral weak currents (neutral boson exchange ?)

- $\nu_\mu(p) + N(q) \to \nu_\mu(p') + N(q')$
- Tiny flavour-changing neutral currents

Can we build a theory of weak interactions
embedding such elements ?

Fermion content

Free massless fermions

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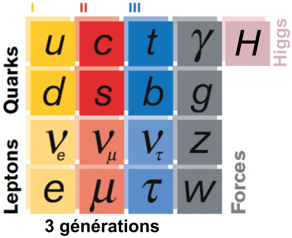
- Right-hd singlets of two types



$$\psi_R = (f_u)_R \qquad \psi_S = (f_d)_R$$

with difference between ”high” and ”low” electric charge fermions

$$f_u = u, c, t, \nu_e, \nu_\mu, \nu_\tau \qquad f_d = d, s, b, e^-, \mu^-, \tau^-$$

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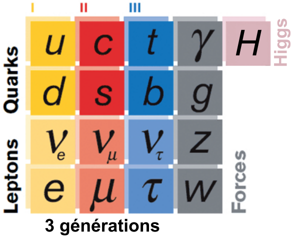

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$$f_u = u, c, t, \nu_e, \nu_\mu, \nu_\tau \qquad f_d = d, s, b, e^-, \mu^-, \tau^-$$

in order to distinguish between

- left-handed doublets involved in charged currents
- right-handed fermions of different charges

Symmetries

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We introduce the $SU(2)_L \otimes U(1)_Y$ symmetry

- $U(1)_Y$: phase β, somehow related to QED
- $SU(2)_L$: rotation $U_L = \exp[i\frac{\vec{\alpha}\vec{\sigma}}{2}]$ affecting only left-hd doublets
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which yields the transformation of the doublets and singlets

$$\psi_L \to e^{iy_L\beta} U_L \psi_L \qquad \psi_R \to e^{iy_R\beta}\psi_R \qquad \psi_S \to e^{iy_S\beta}\psi_S$$

Historically, many attempts with different symmetry groups

Gauge bosons

Promoting $SU(2)_L \otimes U(1)_Y$ to local symmetry, thus covariant deriv

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$$D_\mu \psi_R = [\partial_\mu - i g' y_R B_\mu]\psi_R \to e^{i y_R \beta(x)} D_\mu \psi_R \qquad [id\ for\ \psi_S]$$

$$B_\mu(x) \to B_\mu(x) + \frac{1}{g'}\partial_\mu \beta(x)$$

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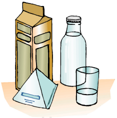
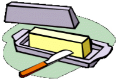
- $SU(2)_L$: $\vec\alpha = \vec\alpha(x) \Longrightarrow$ 3 bosons W^i_μ in $W_\mu(x) = \frac{\vec\sigma}{2}\vec{W}_\mu(x)$

$$D_\mu\psi_L = [\partial_\mu - igW_\mu - ig' y_L B_\mu]\psi_L \to e^{iy_L\beta(x)} U_L(x) D_\mu\psi_L$$

$$W_\mu(x) \to U_L(x)W_\mu(x)U_L^\dagger(x) - \frac{i}{g}\partial_\mu U_L(x)U_L^\dagger(x)$$





Consequences for the interactions

Charged currents

Write down the Lagrangian for fermions with covariant derivatives

$$\mathcal{L} = \sum_{j=L,R,S} i\bar{\psi}_j\gamma^\mu D_\mu\psi_j \Longrightarrow \text{free} + g\bar{\psi}_L\gamma^\mu W_\mu\psi_L + g' B_\mu \sum_{j=L,R,S} y_j\bar{\psi}_j\gamma^\mu\psi_j$$

The interaction term involves the

- 3 bosons related to $SU(2)_L$

$$W_\mu = \frac{\vec{\sigma}}{2}\vec{W}_\mu = \frac{1}{2}\begin{pmatrix} W_\mu^3 & \sqrt{2}W_\mu^\dagger \\ \sqrt{2}W_\mu & -W_\mu^3 \end{pmatrix} \qquad W_\mu = (W_\mu^1 + iW_\mu^2)/\sqrt{2}$$

- 1 boson related ot $U(1)_Y$: B_μ

Charged currents

In the interaction term $g\bar{\psi}_L\gamma^\mu W_\mu \psi_L + g' B_\mu \sum_{j=L,R,S} y_j \bar{\psi}_j \gamma^\mu \psi_j$

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select charged current processes

$$\mathcal{L}_{CC} = \frac{g}{2\sqrt{2}} W_\mu^\dagger[\bar{q}_u\gamma^\mu(1-\gamma_5)q_d + \bar{\nu}_\ell\gamma^\mu(1-\gamma_5)\ell] + h.c.$$

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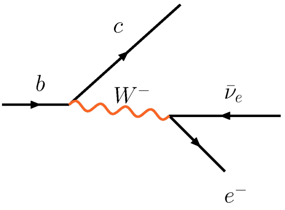
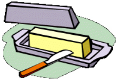
- Mediated by two charged bosons W^+ and W^-
- Quark and lepton universality (one coupling)
- At low energies, reduces to $g^2/M_W^2 \to G_F$ (Fermi constant)
- Left-handed interaction



Neutral currents: the photon

$$\mathcal{L}_{NC} = g\bar{\psi}_L\gamma^\mu W^3_\mu \frac{\sigma_3}{2}\psi_L + g' B_\mu \sum_{j=L,R,S} y_j \bar{\psi}_j\gamma^\mu\psi_j$$



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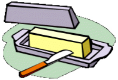

2 neutral bosons mixing to yield physical gauge bosons

$$\begin{pmatrix} W^3_\mu \\ B_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix}$$

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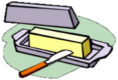

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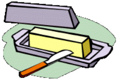

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provided that the following relations hold

- Weinberg angle: $e = g\sin\theta_W = g'\cos\theta_W = \frac{gg'}{\sqrt{g^2+g'^2}}$
- Hypercharge: $y_L = Q_{f_u} - \frac{1}{2} = Q_{f_d} + \frac{1}{2}$, $y_R = Q_{f_u}$, $y_S = Q_{f_d}$

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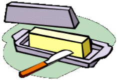

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Neutral currents: the Z boson

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In addition to the photon part, $\mathcal{L}_{NC}$ contains interactions for Z^μ

$$\begin{aligned}\mathcal{L}_{NC}^{Z} &= \frac{e}{\sin\theta_W \cos\theta_W} Z_\mu \left[\bar\psi_L \gamma^\mu \frac{\sigma_3}{2}\psi_L - \sin^2\theta_W \sum_{j=L,R,S} \bar\psi_j \gamma^\mu Q_j \psi_j\right] \\ &= \frac{e}{\sin 2\theta_W} Z_\mu \sum_f \bar f \gamma^\mu [v_f - a_f \gamma_5] f\end{aligned}$$

where fermions f are quarks and leptons containing both f_L and f_R

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\end{aligned}
$$

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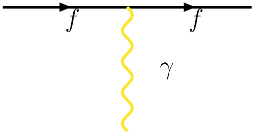
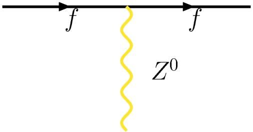
	u, c, t	d, s, b	ν_e, ν_μ, ν_τ	e^-, μ^-, τ^-
$2v_f$	$1 - \frac{8}{3}\sin^2\theta_W$	$-1 + \frac{4}{3}\sin^2\theta_W$	1	$-1 + 4\sin^2\theta_W$
$2a_f$	1	-1	1	-1

Neutral currents: gauge bosons



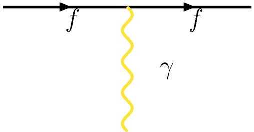
eQ_f



$\frac{e}{2\sin\theta_W}(v_f - a_f\gamma_5)$

$$\mathcal{L}_{NC} = eA_\mu \sum_j \psi_j \gamma^\mu Q_j \psi_j + \frac{e}{\sin 2\theta_W} Z_\mu \sum_f \bar{f}\gamma^\mu [v_f - a_f\gamma_5] f$$

Neutral currents: gauge bosons



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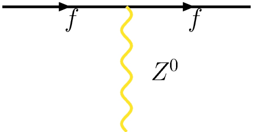
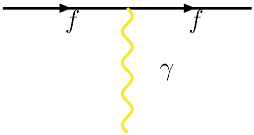


$\frac{e}{2\sin\theta_W}(v_f - a_f\gamma_5)$

$$\mathcal{L}_{NC} = eA_\mu \sum_j \psi_j \gamma^\mu Q_j \psi_j + \frac{e}{\sin 2\theta_W} Z_\mu \sum_f \bar{f}\gamma^\mu [v_f - a_f\gamma_5] f$$

- Weinberg angle only in vector part v_f (“electromagnetic” rotation)

Neutral currents: gauge bosons



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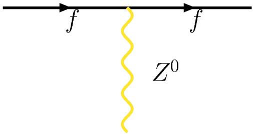

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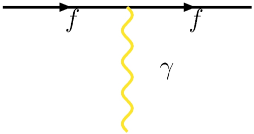

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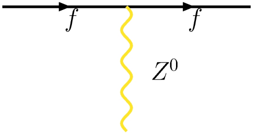

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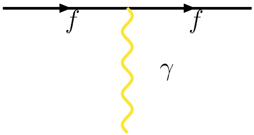
- Weinberg angle only in vector part v_f (“electromagnetic” rotation)
- $v_{\nu_\ell} = a_{\nu_\ell}$: no interaction for right-handed neutrinos
  $\Longrightarrow$Sterile (component of) neutrinos
- No flavour-changing neutral currents from Z and γ-exchange
  $\Longrightarrow$Occur only through loop effects in the SM (small)

Couplings with fermions



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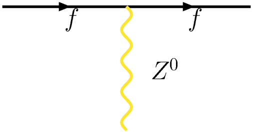
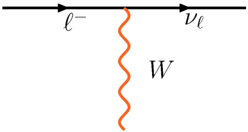
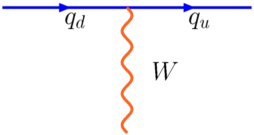


$$\frac{e}{\sin 2\theta_W}(v_f - a_f\gamma_5)$$



$$\frac{g}{2\sqrt{2}}(1-\gamma_5)$$



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Self-couplings

Let us introduce the field tensors

$$W^{\mu\nu} = \partial^\mu W^\nu - \partial^\nu W^\mu - ig[W^\mu, W^\nu] \to U_L W^{\mu\nu} U_L^\dagger$$

$$B^{\mu\nu} = \partial^\mu B^\nu - \partial^\nu B^\mu \to B^{\mu\nu}$$

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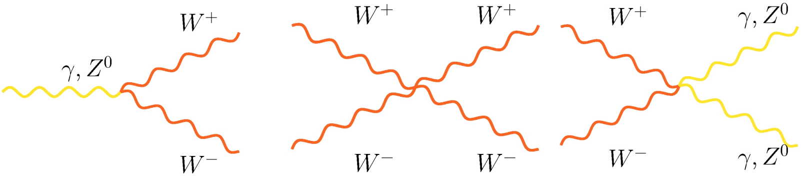
The kinetic part of the Lagrangian $\mathcal{L}_K = -\frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \frac{1}{4} \vec{W}^{\mu\nu} \vec{W}_{\mu\nu}$

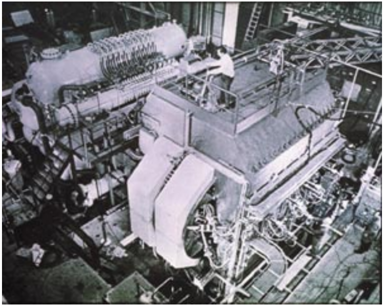


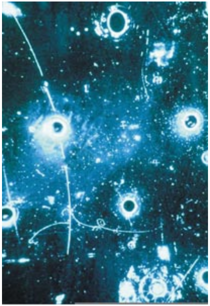
contains three and four-boson couplings
(W^3, B combinations of A, Z)

Experimental signatures

Indirect evidence

- 1960's: Many electroweak models in competition, including Glashow, Weinberg and Salam's, predicting:
  a photon, 2 charged W^+ and W^-, 1 neutral boson Z^0
- 1973: Gargamelle (CERN bubble chamber) observes neutral currents events $\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-$, signature of Z^0

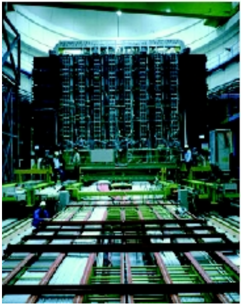


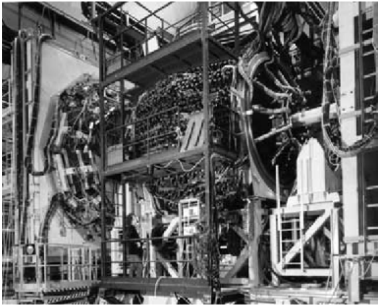


But only indirect evidences for the weak gauge bosons…

Finding the weak gauge bosons

- End 1970's: building of UA1 and UA2 experiments at CERN to detect gauge bosons in $p\bar{p}$ collisions





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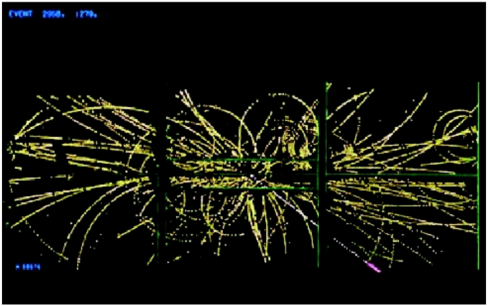
- End 1983: around 12 Z^0- and 100 W-decays are clearly identified



The three weak gauge bosons do exist !

Masses
(the unexpected power of gauge symmetry)

Masses

- $\mathcal{L}_{m_b} = \frac{1}{2} m_b^2 b^\mu b_\mu$ not invariant under gauge transformations:

$$W_\mu(x) \to U_L(x) W_\mu(x) U_L^\dagger(x) - \frac{i}{g'} \partial_\mu U_L(x) U_L^\dagger(x)$$

All the masses of gauge bosons should vanish but

$$m_\gamma = 0 \qquad m_W = 80 \text{ GeV} \qquad m_Z = 91 \text{ GeV}$$

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Something has gone wrong... All the particles are massless !

End of part III