Standard Model

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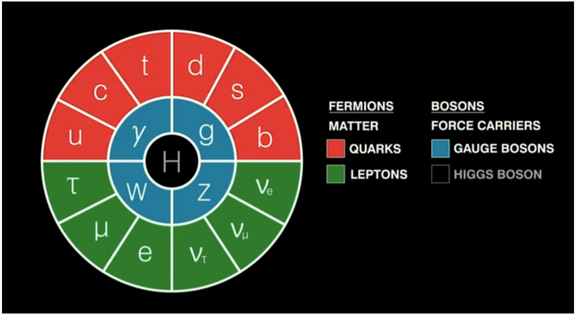
20 February 2017

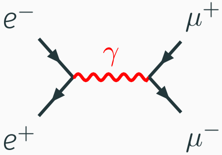
CoEPP Graduate School

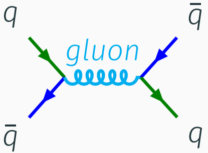
THE UNIVERSITY OF SYDNEY

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

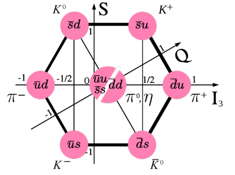
The Standard Model



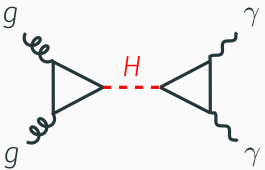


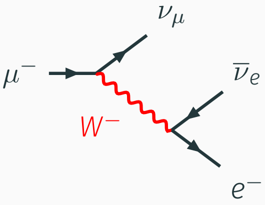


How do we make sense out of this?



Wikipedia





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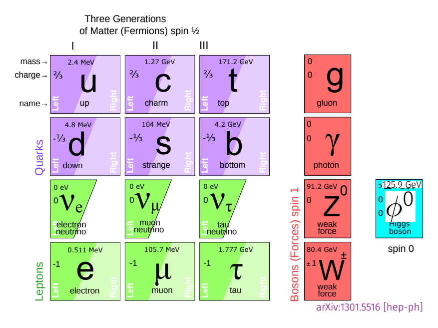

Two chiralities

- left-handed

$$Q = \begin{pmatrix} u \\ d \end{pmatrix} \qquad L = \begin{pmatrix} \nu \\ e \end{pmatrix}$$

- and right-handed
  $u_R \equiv \bar{u}^\dagger, d_R \equiv \bar{d}^\dagger, e_R \equiv \bar{e}^\dagger$

Natural Units: $\hbar = c = k_B = 1$

	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$	spin
Q	3	2	$\frac{1}{6}$	
$\bar{u}$	$\bar{3}$	1	$-\frac{2}{3}$	
$\bar{d}$	$\bar{3}$	1	$\frac{1}{3}$	$(\frac{1}{2}, 0)$
L	1	2	$-\frac{1}{2}$	
$\bar{e}$	1	1	1	
Φ	1	2	$\frac{1}{2}$	$(0, 0)$
G	8	1	0	
W	1	3	0	$(\frac{1}{2}, \frac{1}{2})$
B	1	1	0	

$$D_\mu \equiv \partial_\mu + igA_\mu$$

Electric charge: $Q = T_3 + Y$

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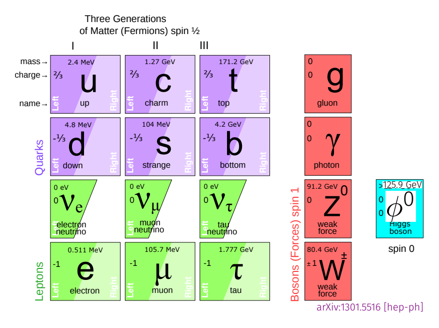

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$$\begin{aligned}\mathcal{L} = &-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ &+ i\psi^\dagger\bar{\sigma}^\mu D_\mu\psi \\ &+ Y_{ij}\psi_i\psi_j\Phi + \text{h. c.} \\ &+ |D_\mu\Phi|^2 - V(\Phi^\dagger\Phi)\end{aligned}$$

$$D_\mu \equiv \partial_\mu + igA_\mu$$

Electric charge: $Q = T_3 + Y$

QED - U(1) Gauge Theory

- Interactions in the SM respect the fundamental symmetries: Poincaré and (internal) gauge symmetries
- The simplest gauge symmetry is a U(1)

$$\mathcal{L}_{QED} = -\frac{1}{4} F_{\mu\nu}F^{\mu\nu} + i\bar{e}^\dagger\bar{\sigma}^\mu D^-_\mu \bar{e} + ie^\dagger\bar{\sigma}^\mu D^+_\mu e + m_e\bar{e}e + m_e\bar{e}^\dagger e^\dagger$$

field strength tensor $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

mass m_e

covariant derivative $D^\pm_\mu = \partial_\mu \pm ieA_\mu$

- Electromagnetic interaction

virtual photon
$k^2 \neq 0$

$$\mathcal{L}_{int} = -e^\dagger\bar{\sigma}_\mu A_\mu e + \bar{e}^\dagger\bar{\sigma}_\mu A_\mu \bar{e}$$

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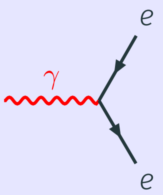

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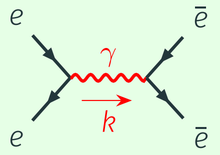

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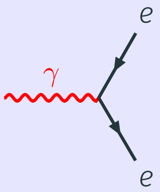

$$\mathcal{L}_{int} = -e^\dagger\bar{\sigma}_\mu A_\mu e + \bar{e}^\dagger\bar{\sigma}_\mu A_\mu \bar{e}$$

QCD - SU(3) Gauge Theory

- Quarks transform under SU(3) as 3
  $\Rightarrow$ each quark flavour comes in three colours.

$$\mathcal{L}_{QCD} = -\frac{1}{4}\sum_A G^A_{\mu\nu} G^{A\mu\nu} + iq^\dagger \bar{\sigma}^\mu D_\mu q \qquad D_\mu = \partial_\mu + ig_s \frac{\lambda^A}{2} G^A_\mu$$

- The Gell-Mann matrices λ^A define SU(3) generators $T^A = \frac{\lambda^A}{2}$

$$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}$$

$$\lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad \lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \quad \lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

- Field strength tensor

$$G_{\mu\nu} = \frac{1}{ig_s}[D_\mu, D_\nu] \Rightarrow G^A_{\mu\nu} = \partial_\mu G^A_\nu - \partial_\nu G^A_\mu - g_s f_{ABC} G^B_\mu G^C_\nu$$

with the structure constants $[T^A, T^B] = i f_{ABC} T^C$

QCD Gauge Interactions

$$G^A_{\mu\nu} = \partial_\mu G^A_\nu - \partial_\nu G^A_\mu - g_s f_{ABC} G^B_\mu G^C_\nu \qquad D_\mu = \partial_\mu + i\frac{g_s}{2}\lambda^A G^A_\mu$$

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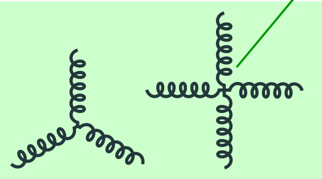
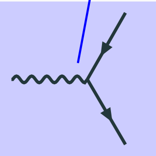
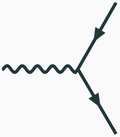


no analogue in QED



analogous to QED

Charge renormalization



Resumming all loops of this type

via solution of β-function $\mu \frac{d\alpha}{d\mu} = b_0 \frac{\alpha^2}{2\pi}$

$$\alpha(q^2) = \frac{\alpha(\mu^2)}{1 - \frac{\alpha(\mu^2)}{4\pi}\, b_0 \, \ln \frac{q^2}{\mu^2}}$$

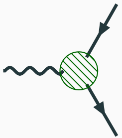
In the SM:

$$b_0^1 = \frac{41}{6} \qquad b_0^2 = -\frac{19}{6} \qquad b_0^3 = -7$$

Note the different signs!

QCD: $b_0^3 = \frac{2}{3} N_f \; -11$

Charge renormalization



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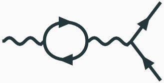

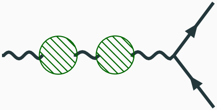

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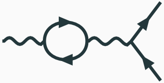

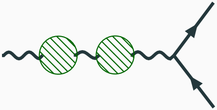

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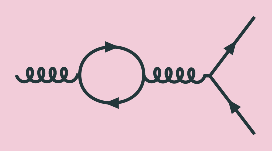

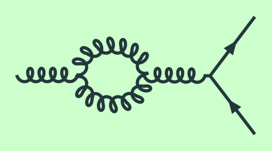

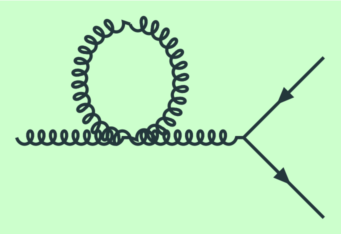

Asymptotic Freedom and Landau Pole

- Evolution of gauge coupling

$$\alpha^{-1}(q^2) = \alpha^{-1}(\mu^2) - \frac{b_0}{4\pi} \ln \frac{q^2}{\mu^2}$$

- The sign of the b_0 is important !

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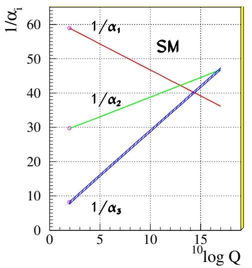

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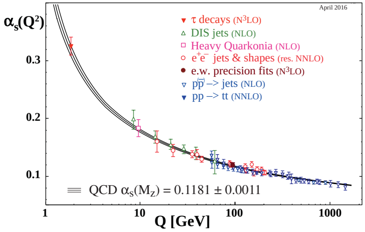


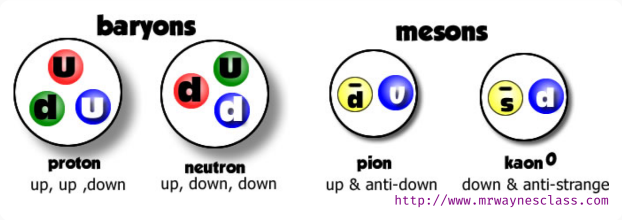
PDG

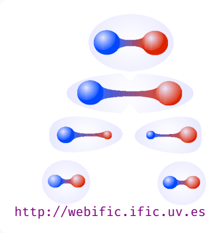
- QCD coupling asymptotically approaches zero [asymptotic freedom]
- If the denominator vanishes, the coupling diverges. [Landau pole]

$$\Lambda_{LP}^2 \equiv \mu^2 e^{-\frac{4\pi}{\alpha(\mu^2) b_0}}$$

QCD Scale and Confinement

- For QCD $\Lambda_c \approx 300\mathrm{MeV}$ is called QCD scale.
- It is believed that non-perturbative physics at this scale leads to confinement of quarks into colour-singlet hadrons





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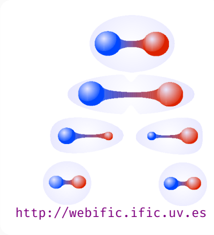
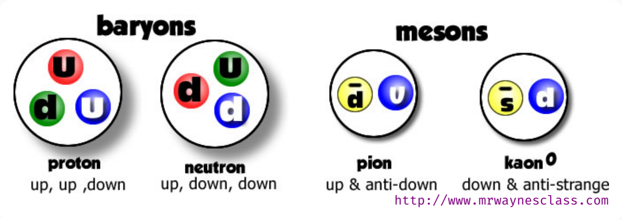
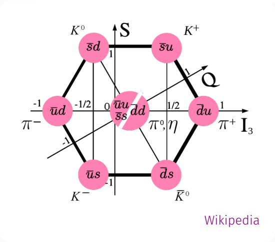
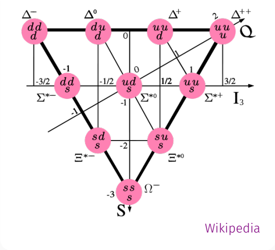
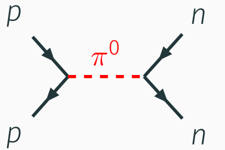










Why SU(3)?

- 3 quarks in baryons explained in SU(3) $3 \times 3 \times 3 = 1 + \ldots$
- Decays of W,Z and $\pi^0 \to \gamma\gamma$ with $\Gamma(\pi^0) \sim N_c^2$
- $e^+e^- \to$ hadrons: $R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_c \sum_q Q_q^2$

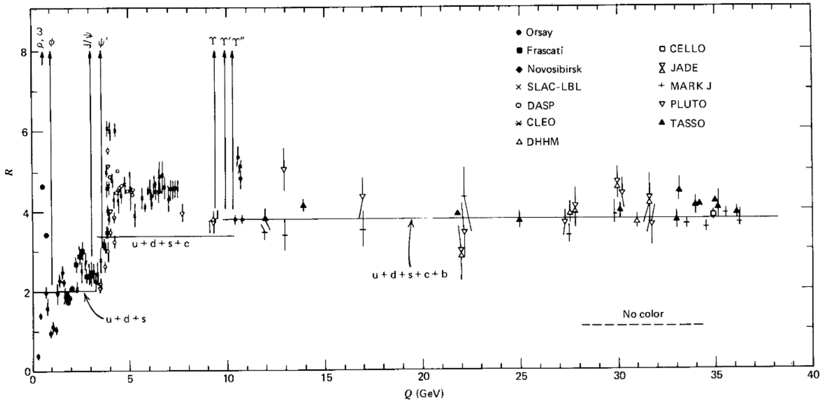


Fig. 11.3 Ratio R of (11.6) as a function of the total e^-e^+ center-of-mass energy. (The sharp peaks correspond to the production of narrov 1^- resonances just below or near the flavor thresholds.)

Halzen and Martin: Quarks and Leptons

Electroweak Theory: $SU(2)_W \times U(1)_Y$

Lagrangian for leptons and electroweak interactions

$$\mathcal{L}_{EW} = -\frac{1}{4} \sum_A W^A_{\mu\nu} W^{A\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + i L^\dagger \bar{\sigma}^\mu D^L_\mu L + i \bar{e}^\dagger \bar{\sigma}^\mu D^e_\mu \bar{e}$$

$SU(2)_W$ gauge bosons $U(1)_Y$ gauge boson   Lepton doublet $L \equiv \begin{pmatrix} \nu_e \\ e \end{pmatrix}$

Covariant derivatives

$$D^L_\mu = \partial_\mu + ig \sum_A W^A_\mu \frac{\sigma^A}{2} + ig' Y_L B^\mu \qquad D^e_\mu = \partial_\mu + ig' Y_e B^\mu$$

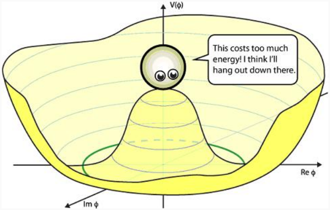
Pauli matrices: $\sigma^1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$ $\sigma^2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$ $\sigma^3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

- Note, only left-handed particles L couple to W_μ
- All fermions massless: Not possible to write Dirac mass term like $L\bar{e}$ nor Majorana mass term like LL.
- Similarly W and Z bosons are massless
- Mass generation $\Leftarrow$ spontaneous symmetry breaking

Potential of complex scalar field

$$V(|\phi(x)|^2) = -\mu^2|\phi(x)|^2 + \lambda|\phi(x)|^4$$

has U(1) symmetry $\phi(x) \to e^{i\alpha(x)}\phi(x)$



- ϕ obtains vacuum expectation value (vev) $\langle 0|\phi|0\rangle = v$

$\Rightarrow$ Vacuum state breaks U(1) symmetry of potential

- Expanding around vacuum state $\phi(x) = v + \frac{\varphi(x)+ig(x)}{\sqrt{2}}$ with $v^2 = \frac{\mu^2}{2\lambda}$ leads to quadratic order in fields

$$V(\varphi, g) = -\lambda v^4 + 2\lambda v^2\varphi(x)^2 + \dots$$

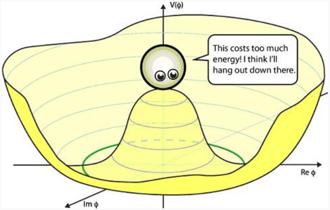
$\Rightarrow$ Spontaneous symmetry breaking

- g is massless and a Goldstone boson
- Spontaneously broken generator $\Rightarrow$ Goldstone boson

Potential of complex scalar field

$$V(|\phi(x)|^2) = -\mu^2|\phi(x)|^2 + \lambda|\phi(x)|^4$$

has U(1) symmetry $\phi(x) \to e^{i\alpha(x)}\phi(x)$



- ϕ obtains vacuum expectation value (vev) $\langle 0|\phi|0\rangle = v$

$\Rightarrow$ Vacuum state breaks U(1) symmetry of potential

- Expanding around vacuum state $\phi(x) = v + \frac{\varphi(x)+ig(x)}{\sqrt{2}}$ with $v^2 = \frac{\mu^2}{2\lambda}$ leads to quadratic order in fields

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Spontaneous Symmetry Breaking: Abelian Higgs model

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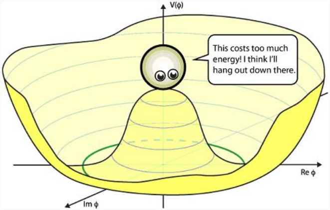

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Higgs Mechanism for U(1) Gauge Symmetry

Kinetic term with $D_\mu = \partial_\mu + igA_\mu$ and $\phi = v + \frac{\varphi + ig}{\sqrt{2}}$

$$\mathcal{L}_{kin} = |D_\mu \phi|^2 = \frac{1}{2}(\partial_\mu \varphi)^2 + \frac{1}{2}(\partial_\mu g)^2 + \sqrt{2} g v A_\mu \partial^\mu g + g^2 v^2 A_\mu A^\mu + \dots$$

- Gauge boson becomes massive: $m_A^2 = 2g^2v^2$
- Mixing term can be removed by gauge transformation g undergoes inhomogeneous transformation $\phi \to e^{i\alpha}\phi$

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Spontaneous Symmetry Breaking in SM

- Same mechanism is at work for Higgs in SM

$$\mathcal{L}_{Higgs} = (D_\mu\Phi)^\dagger D^\mu\Phi + \mu^2\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2$$

  where $D_\mu = \partial_\mu + ig\sum_A \frac{\sigma^A}{2}W_\mu^A + ig'YB_\mu$

- vev $\langle\Phi\rangle \equiv \langle 0|\Phi|0\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix}$ with $v = (\sqrt{2}G_F)^{-1/2} \simeq 246$ GeV
- Mass term for gauge boson

$$\mathcal{L} =$$

$$W_\mu^\pm = \frac{1}{\sqrt{2}}\left(W_\mu^1 \mp iW_\mu^2\right) \quad \text{with mass} \quad m_W = g\frac{v}{2}$$

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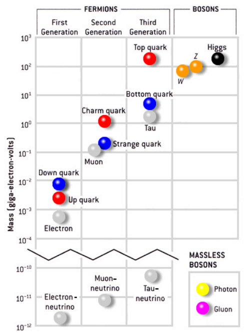
Fermion Masses

- Yukawa interaction $[\tilde{\Phi} \equiv i\sigma_2 \Phi^*]$

$$\mathcal{L}_Y = Y_u^{ij} Q_i \bar{u}_j \Phi + Y_d^{ij} Q_i \bar{d}_j \tilde{\Phi} + Y_e^{ij} L_i \bar{e}_j \tilde{\Phi}$$



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$$q' = U_{qL} q \quad \bar{q}' = U_{qR} \bar{q} \quad \Rightarrow \quad U_{uL}^T M_u U_{uR} = \text{diag}$$

q' are mass eigenstates

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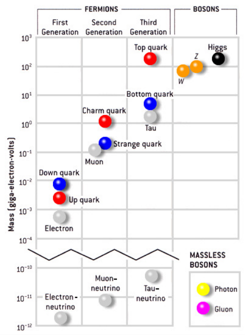

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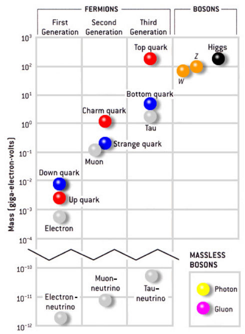

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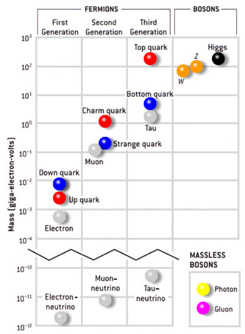

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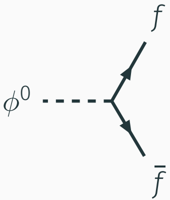

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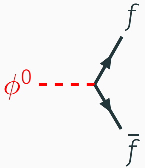
Higgs Couplings

- to same-flavour fermions
- to two gauge bosons
- Two Higgs coupling to …
- Loop induced couplings to vector bosons



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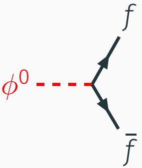

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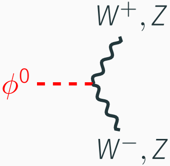

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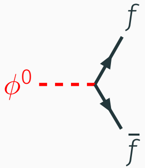

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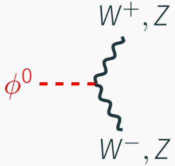

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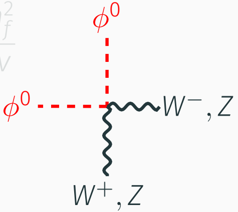

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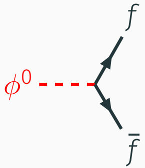

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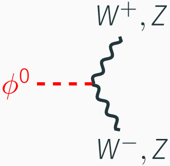

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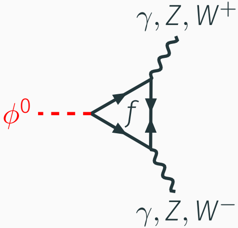

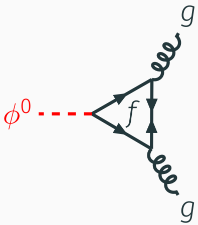

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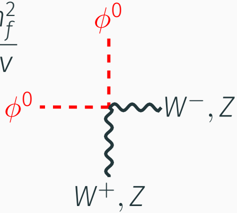

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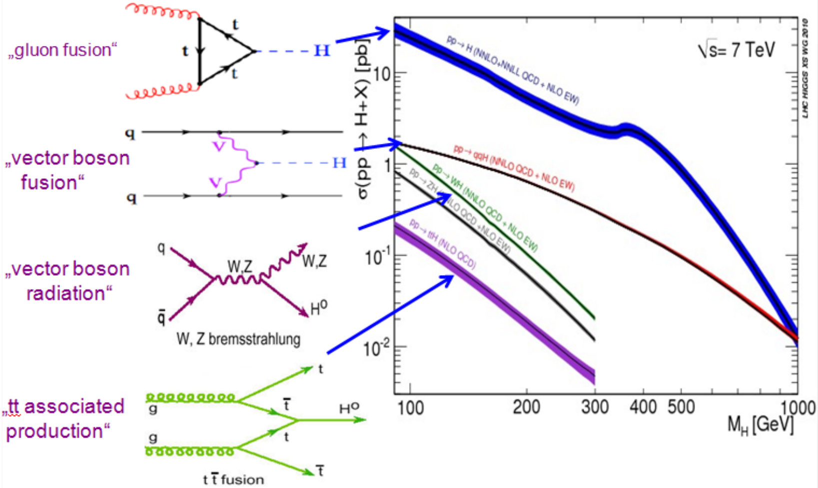
Higgs production



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Interactions of fermions with gauge bosons [$e = g\sin\theta_w$]

$$-\mathcal{L}_{W,Z,\gamma} = g\left(W^+_\mu J^{\mu+}_W + W^-_\mu J^{\mu-}_W + Z^0_\mu J^\mu_Z\right) + eA_\mu J^\mu_{em}$$

Fermionic kinetic terms $i\psi^\dagger\bar{\sigma}^\mu D_\mu\psi$ yield electroweak currents

$$J^{\mu+}_W = \frac{1}{\sqrt{2}}\left(\nu^\dagger\bar{\sigma}^\mu e + V_{ij}u'^\dagger_i\bar{\sigma}^\mu d'_j\right) \qquad Q = T^3 + Y$$

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- Rotation of LH fields $f' = U_{fL}f$ yields flavour-changing charged currents: Cabibbo-Kobayashi-Maskawa (CKM) matrix $V = U^\dagger_{uL}U_{dL}$
- No couplings of Z boson to different quark flavours
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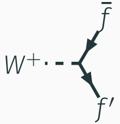

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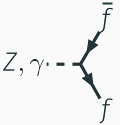

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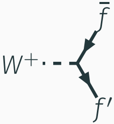

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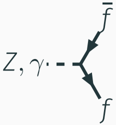

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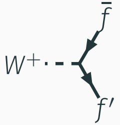
Weak Interactions and CKM Matrix

Interactions of fermions with gauge bosons [$e = g \sin\theta_w$]

$$-\mathcal{L}_{W,Z,\gamma} = g\left(W^+_\mu J^{\mu+}_W + W^-_\mu J^{\mu-}_W + Z^0_\mu J^\mu_Z\right) + eA_\mu J^\mu_{em}$$

Fermionic kinetic terms $i\psi^\dagger\bar{\sigma}^\mu D_\mu\psi$ yield electroweak currents

$$J^{\mu+}_W = \frac{1}{\sqrt{2}}\left(\nu^\dagger\bar{\sigma}^\mu e + V_{ij}u_i'^\dagger\bar{\sigma}^\mu d_j'\right) \qquad Q = T^3 + Y$$



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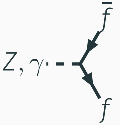

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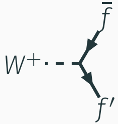

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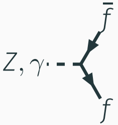

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- Drell-Yan process
- Beta decay
- Fermi theory of beta decay recovered for $p^2 \ll m_W^2$ with

$$G_F = \frac{\sqrt{2}}{8}\frac{g^2}{m_W^2}$$

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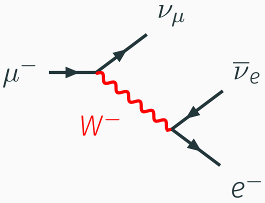

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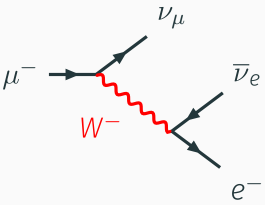

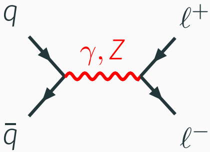

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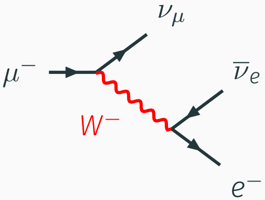

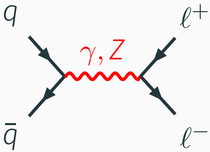

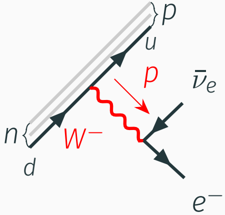

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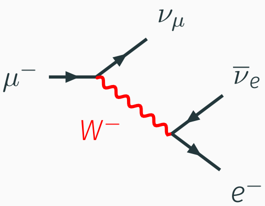

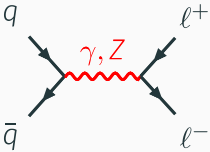

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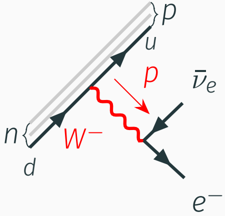

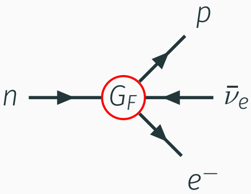

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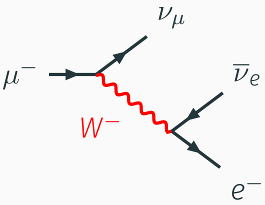

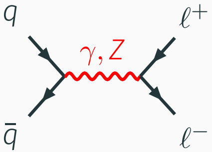

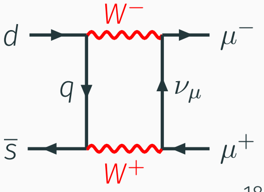

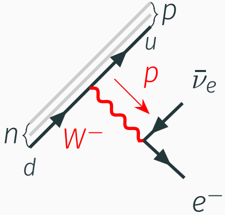

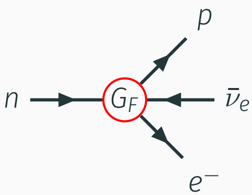

Open questions

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- Why hierarchy between electroweak scale and Planck scale?
- Is there a unification of forces?
- Why are there three generations?
- Neutrinos oscillate and thus have mass $m_\nu \lesssim 0.1\mathrm{eV}$.
- What is dark matter?
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Weinberg Operator and Neutrino Mass

- Neutrinos are neutral and can be their own antiparticle

$\Rightarrow$ i.e. Majorana fermions with mass term $\frac{1}{2} m_\nu \nu\nu + \mathrm{h.c.}$

- ν in lepton doublet $\rightarrow$ Higgs mechanism

$$\mathcal{L}_\nu = \frac{1}{2}\frac{\kappa}{\Lambda} L\Phi L\Phi + \mathrm{h.c.} \quad \xrightarrow{\Phi \to \langle\Phi\rangle} \quad \frac{1}{2}\frac{\kappa v^2}{2\Lambda}\nu\nu + \mathrm{h.c.}$$

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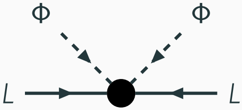

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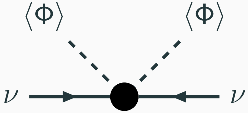

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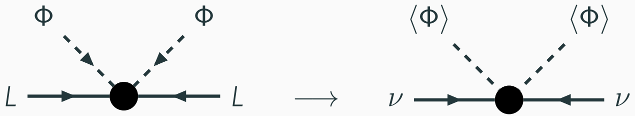

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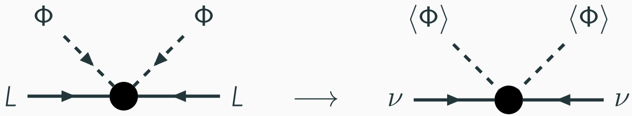

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