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The Standard Model of particle physics

Michael Krämer (RWTH Aachen University)

Bibliography

- I.J.R. Aitchison and A.J.G. Hey, "Gauge Theories in Particle Physics", IoP Publishing.
- R.K. Ellis, W.J. Stirling and B.R. Webber, "QCD And Collider Physics," Cambridge Monogr. Part. Phys. Nucl. Phys. Cosmol. 8 (1996) 1.
- D. E. Soper, Basics of QCD perturbation theory, arXiv:hep-ph/0011256.
- Lectures by Keith Ellis, Douglas Ross, Adrian Signer, Robert Thorne and Bryan Webber (thanks!).

The Standard Model

The Standard Model Lagrangian is determined by symmetries

- space-time symmetry: global Poincaré-symmetry
- internal symmetries: local $SU(n)$ gauge symmetries

$$
\begin{aligned}
\mathcal{L}_{\mathrm{SM}} = \; & -\tfrac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + i\bar{\psi}\not{D}\psi && \text{gauge sector} \\
& + |DH|^2 - V(H) && \text{EWSB sector} \\
& + \psi_i \lambda_{ij} \psi_j H + \mathrm{h.c.} && \text{flavour sector} \\
& + N_i M_{ij} N_j && \nu\text{-mass sector}
\end{aligned}
$$

Outline

- QED and QCD as gauge theories
- QCD for the LHC
- Breaking gauge symmetries:
  the Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism

Spontaneous symmetry breaking

A $SU(n)$ gauge theory

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} + \overline{\psi}^i \left(i\gamma^\mu D_\mu - m \right)^j_i \psi_j$$

has massless gauge bosons A^a_μ:

To preserve gauge invariance of the Lagrangian, the A^a_μ transform under gauge transformations as

$$A^a_\mu \to A^a_\mu - f^{abc} A^b_\mu(x) \omega^c(x) + \frac{1}{g} \left[\partial_\mu \omega^a(x) \right] ,$$

and thus a mass term

$$\mathcal{L} \supset M_A^2 \, A^a_\mu A^{a\,\mu}$$

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This is what we want for QED (massless photon) and QCD (massless gluons), but not for a gauge theory of the weak interactions.

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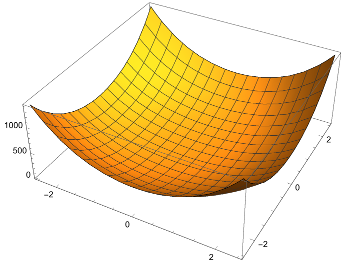

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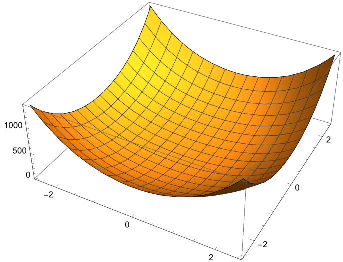

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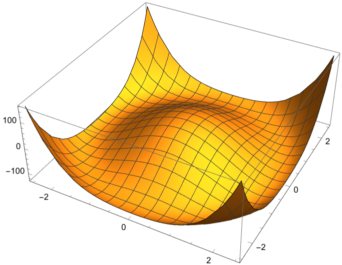

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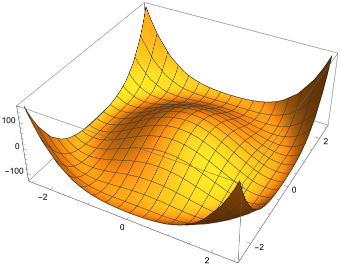

The potential is symmetric under rotations, but the ground state (any point along the circle $|\vec{r}| = \sqrt{-\mu^2/2\lambda}$) is not.

Let us consider a gauge theory with a complex scalar field Φ:

$$\mathcal{L} = (D_\mu \Phi)^* D^\mu \Phi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - V(\Phi)$$

and

$$V(\Phi) = -\mu^2 \Phi^* \Phi + \lambda |\Phi^* \Phi|^2$$

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The symmetry breaking occurs in the choice made for the value of Θ. For any specific choice of Θ we have

$$\Phi \to e^{-i\omega}\Phi = e^{-i\omega} e^{i\Theta} \frac{v}{\sqrt{2}} = e^{i(\Theta - \omega)} \frac{v}{\sqrt{2}} = e^{i\Theta'} \frac{v}{\sqrt{2}} ,$$

i.e. the ground state is not invariant under gauge transformations.

In QFT we would say that the field Φ has a non-zero vacuum expectation value:

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Let us expand Φ around the vacuum expectation value,

$$\Phi(x) = \frac{\rho(x)}{\sqrt{2}} e^{i\phi(x)/v} = \frac{1}{\sqrt{2}}(v + H(x))e^{i\phi(x)/v} \approx \frac{1}{\sqrt{2}}(v + H(x) + i\phi(x)),$$

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The potential becomes

$$V = \mu^2 H^2 + \mu\sqrt{\lambda}(H^3 + \phi^2 H) + \frac{\lambda}{4}(H^4 + \phi^4 + 2H^2\phi^2) + \frac{\mu^4}{4\lambda}\,.$$

There is a mass term for the field H:

$$V \supset \mu^2 H^2 \equiv \frac{M_H}{2} H^2 \quad \text{with} \quad M_H = \sqrt{2}\mu\,,$$

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but no mass term for the field ϕ.

Thus ϕ represents a massless particle, called “Goldstone boson”.

For the kinetic term we find

$$(D_\mu\Phi)^* D^\mu\Phi \supset \frac{1}{2}\partial_\mu H\partial^\mu H + \frac{1}{2}g^2v^2A_\mu A^\mu + g^2vA_\mu A^\mu H\,.$$

The gauge boson has acquired a mass term:

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Note that the Goldstone boson ϕ is unphysical and can be removed from the Lagrangian by choosing a particular gauge (unitary gauge).

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Let us count the number of degrees of freedom:

- A complex scalar field Φ (2) + a massless gauge boson A_μ (2) = 4
- A real scalar field H (1) + a massive gauge boson A_μ (3) = 4

The 2 d.o.f. of the complex field Φ correspond to the field H and the longitudinal component of the massive gauge boson.

The Standard Model with one family

Empirically we know that the weak interactions violate parity and that the couplings are of the form vector minus axial-vector ($V - A$):

$$\overline{\psi}\gamma_\mu\psi - \overline{\psi}\gamma_\mu\gamma_5\psi\,,$$

where $\gamma_5 \equiv i\gamma^0\gamma^1\gamma^2\gamma^3$.

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We define left- and right-chiral components of spinor fields as

$$\psi = \psi_L + \psi_R \quad \text{where} \quad \psi_{L/R} = \frac{1}{2}(1 \mp \gamma^5)\psi\,.$$

[In the limit where the fermions are massless, chirality becomes helicity, which is the projection of the spin on the direction of the motions.]

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The $(V - A)$ structure implies that only left-chiral fermions participate in the weak interactions:

$$\overline{\psi}\gamma_\mu\psi - \overline{\psi}\gamma_\mu\gamma_5\psi = \overline{\psi}\gamma_\mu(1-\gamma_5)\psi = \overline{\psi}_L\gamma_\mu\psi_L\,.$$

To write down a gauge invariant Lagrangian for the (electro-)weak interactions, we have to choose the gauge group. Let us try

$$SU(2)_L \times U(1)_Y \, .$$

The $SU(2)_L$ group has 3 generators, $T^a = \sigma_a/2$, a gauge coupling denoted by g and three gauge bosons W^a_μ. It is called weak isospin.

The $U(1)$ group is not the gauge group of QED, but that of hypercharge Y. The corresponding coupling and gauge boson are denoted by g' and B^μ.

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As matter content (for the first family), we have

$$q_L \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix};\, u_R;\, d_R;\, l_L \equiv \begin{pmatrix} \nu \\ e_L \end{pmatrix};\, e_R;\, \nu_R \,.$$

The model is constructed such that $SU(2)_L$ gauge transformations only act on q_L and l_L,

$$q_L \to q'_L = e^{-i\omega^a T^a} q_L \quad \text{and} \quad l_L \to l'_L = e^{-i\omega^a T^a} l_L \,,$$

while u_R, d_R, ν_R, and e_R are $SU(2)_L$ singlets and do not couple to the corresponding gauge bosons W^a_μ.

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Under $U(1)_Y$, the matter fields transform as $\psi \to \psi' = e^{-i\omega Y_\psi} \psi$.

The Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism

We introduce a scalar field which transforms as a doublet under $SU(2)_L$, and which has a potential of the form

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$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

so that

$$D_\mu \Phi = \frac{1}{\sqrt{2}} \left(\partial_\mu + i \frac{g}{2} \begin{pmatrix} W_\mu^3 & \sqrt{2} W_\mu^- \\ \sqrt{2} W_\mu^+ & -W_\mu^3 \end{pmatrix} + i \frac{g'}{2} B_\mu \right) \begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

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and thus

$$|D_\mu \Phi|^2 \supset \frac{1}{2} (\partial_\mu H)^2 + \frac{g^2 v^2}{4} W^{+\mu} W_\mu^- + \frac{v^2}{8} \left(g W_\mu^3 - g' B_\mu \right)^2$$

where $W_\mu^\pm = (W_\mu^1 \pm W_\mu^2)/\sqrt{2}$.

Thus the gauge bosons W_μ^3 and B_μ mix, and the physical mass eigenstates are the linear combinations

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\begin{aligned}
Z_\mu &\equiv \cos\theta_w W_\mu^3 - \sin\theta_w B_\mu \\
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We can read off the masses of the gauge bosons,

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One can show that the quantum numbers of the $SU(2)_L$, $U(1)_Y$ and $U(1)_{\rm em}$ gauge groups are connected through $Q = Y + T^3$.

Fermion masses

In our free Dirac Lagrangian, we included a mass term for the fermions

$$\mathcal{L} \supset m\overline{\psi}\psi = m\overline{\psi}_L\psi_R + m\overline{\psi}_R\psi_L \,.$$

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$$-\frac{Y_e}{\sqrt{2}}(v+H)\left(\overline{e}_L e_R + \overline{e}_R e_L\right) = -\frac{Y_e}{\sqrt{2}}(v+H)\,\overline{e}e = -m_e\overline{e}e - \frac{m_e}{v}H\overline{e}e \,,$$

where

$$m_e \equiv \frac{Y_e v}{\sqrt{2}} \quad \text{or} \quad Y_e = \frac{\sqrt{2}m_e}{v} = g\frac{m_e}{\sqrt{2}M_W}$$

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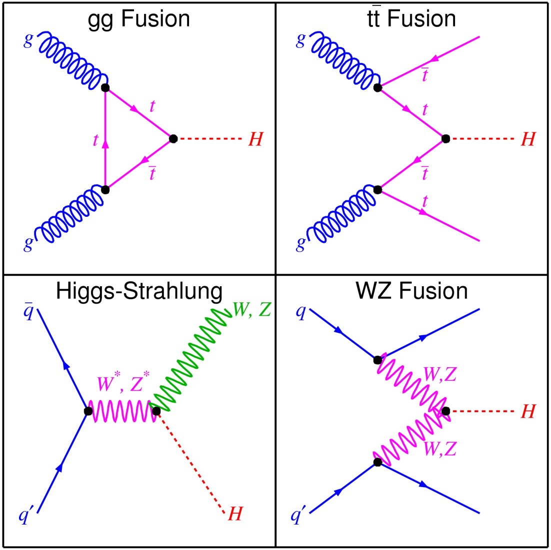
where

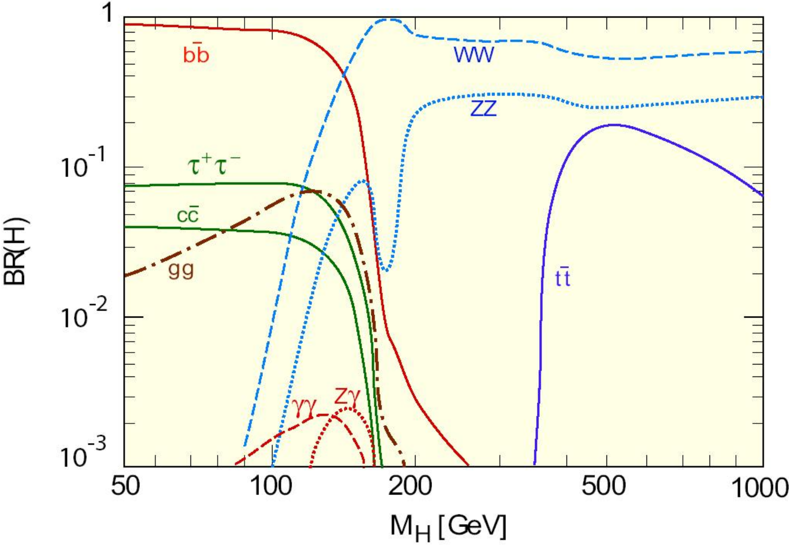
$$m_e \equiv \frac{Y_e v}{\sqrt{2}} \quad \text{or} \quad Y_e = \frac{\sqrt{2}m_e}{v} = g\frac{m_e}{\sqrt{2}M_W}$$

The strength of the interaction between the Higgs particle and the fermions is proportional to the fermion mass.

The Higgs is produced through its interaction with heavy particles



The Higgs likes to decay to heavy particles



Classifying free parameters

The free parameters in the electroweak Standard Model for one generation are

- the two gauge couplings g, g' for the $SU(2)_L$ and $U(1)_Y$ gauge groups;
- the two parameters μ and λ in the potential $V(\Phi)$;
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Adding the QCD sector and two more generations of quarks and leptons, the Standard Model contains at least 26 free parameters:

- 3 gauge couplings
- 6 quark masses
- 6 lepton masses
- 3+3 mixing angles
- 1+1 CP-violating phases
- 1 W or Z mass
- 1 Higgs mass
- 1 CP-violating angle

Physics beyond the Standard Model?

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  What is the origin of particle masses? Is it the SM Higgs field?

  What stabilizes the Higgs mass?

  What sets the scale of fermion masses?

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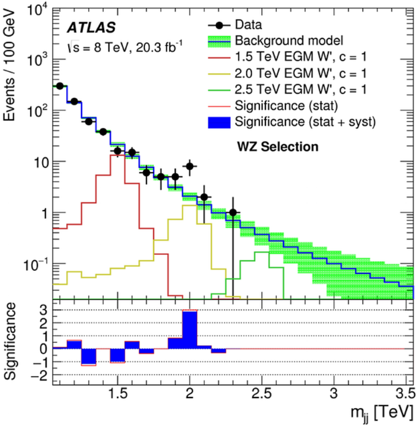
- Cosmological problems:

  What is the origin of the baryon-antibaryon asymmetry?
  What is the nature of dark matter and dark energy?

LHC phenomenology 2015: new discoveries?



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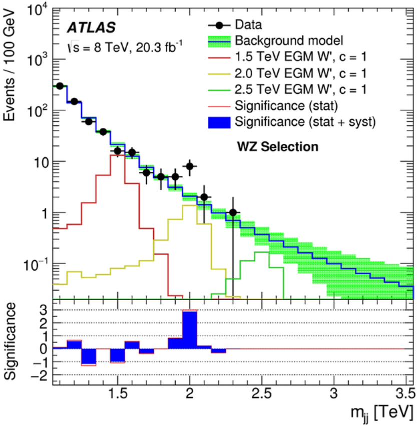

"It is also a good rule not to put overmuch confidence in the observational results that are put forward until they are confirmed by theory." (Sir Arthur Eddington)

Thanks
& enjoy the summer at CERN

Questions, suggestions etc.? Please get in touch!

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