How the Brout-Englert-Higgs Field Gives Mass to the Weak Bosons

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Goal

Illustrating the Higgs mechanism on a high school level while avoiding common misconceptions.

Classical Example: Pendulum

The Lagrangian L is the difference between kinetic and potential energy of a system,

$$L = E_{\text{kin}} - E_{\text{pot}}.$$

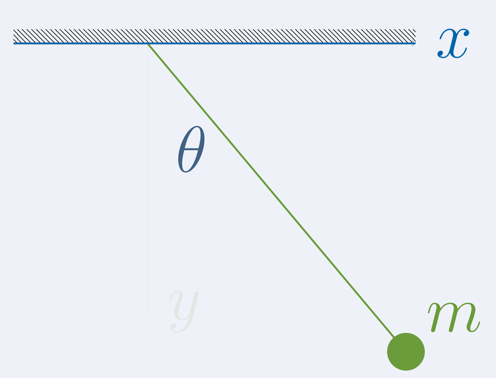
We define the action to be

$$S(q) = \int L(t, q(t), q'(t))\, dt.$$

Using the principle of least action ($\delta S \equiv 0$) we get the Euler-Lagrange equations of motion.

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{q}} = \frac{\partial L}{\partial q}$$

$$\Rightarrow \qquad \theta(t) = \theta_0\, e^{i\omega t}$$



Lagrangian $\mathscr{L}$ for Field Theory

ϕ is the Higgs field, and A_μ is the $W^\pm$ or Z^0 field.

$$\mathscr{L} = \partial^\mu\phi\, \partial_\mu\phi + \mu^2\phi^2 - \frac{\lambda}{2}\,\phi^4 - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - g\,\phi^2 A^\mu A_\mu$$

Kinetic and potential energy are expressed through kinetic, mass and interaction terms.

Kinetic terms are quadratic in the field and contain derivatives.

Mass terms are quadratic, but without derivatives.

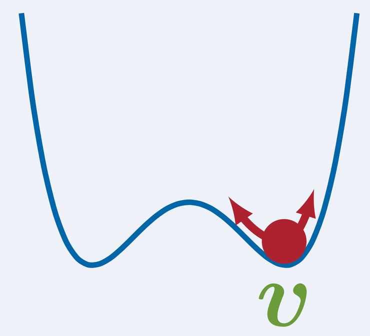
Interaction terms are cubic or quartic in the field and might contain derivatives.

Higgs potential

$$E_{\text{pot}} = -\mu^2\phi^2 + \frac{\lambda}{2}\,\phi^4$$

The potential for the Brout-Englert-Higgs field has non-zero minima. This means that the field will not be zero in the vacuum, when it is at its lowest energy: $\langle\phi\rangle = v \neq 0$.

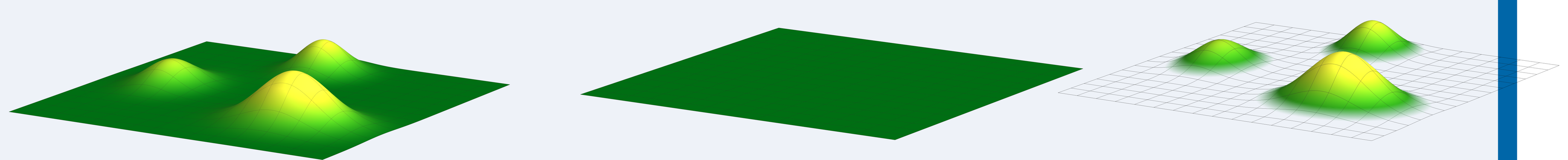
Normally a potential has one unique minimum, located where the field is zero. A particle is then described by small fluctuations around this minimum. The Higgs potential is different: where the BEH field is zero, the potential has a local **maximum** instead, which is unstable.



In this case one of the two minima (named v) has to be chosen as a basis to fluctuate around.

Shifting the Higgs

Instead of treating the BEH field ϕ as fluctuations around the unstable maximum (which would be infeasible), the field is shifted down. We then redefine the field as a combination of the original vacuum expectation value v and a "regular" field σ (which are the fluctuations around the chosen minimum).



$$\boldsymbol{\phi} \quad = \quad \boldsymbol{v} \quad + \quad \boldsymbol{\sigma}$$

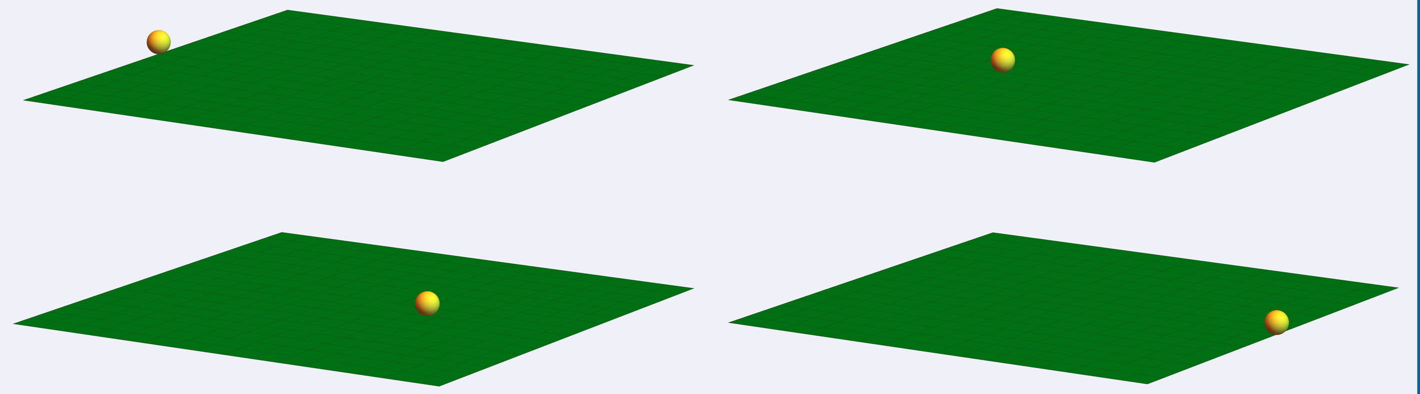
The new field has now vanishing vacuum expectation: $\langle\sigma\rangle = 0$.

Giving mass

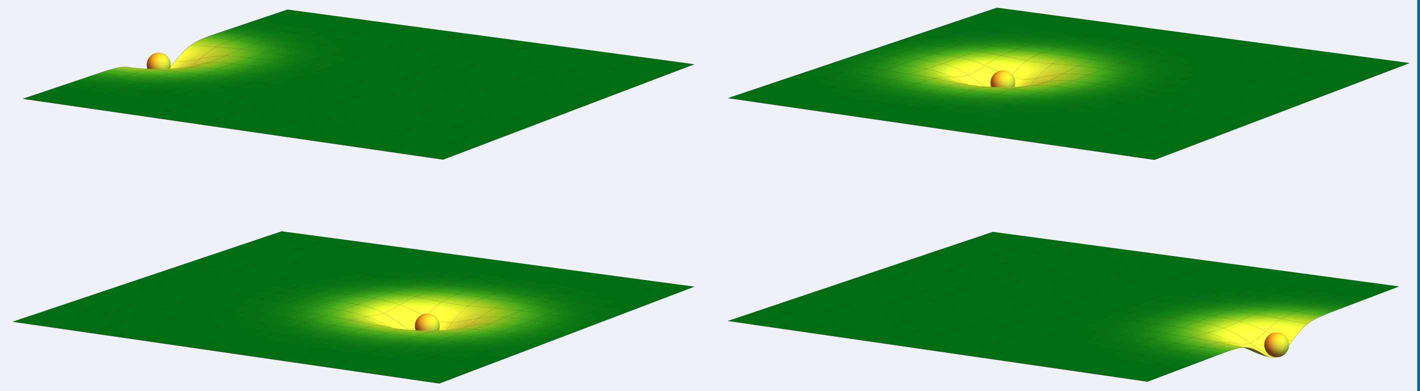
By inserting the new expression for the Higgs field into the Lagrangian, we discover a **mass term** for the W field that wasn't present before.

$$\mathscr{L} = \partial^\mu\sigma\,\partial_\mu\sigma - 2\mu^2\sigma^2 + 2\mu\sqrt{\lambda}\,\sigma^3 + \frac{\lambda}{2}\,\sigma^4 - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$
$$- \boldsymbol{g v^2 A_\mu A^\mu} - 2\,g\,v\,\sigma A_\mu A^\mu - g\sigma^2 A_\mu A^\mu$$

It is not the Higgs boson that gives mass, but the vacuum expectation value v that is extracted from the Brout-Englert-Higgs field.



Massless particles are not influenced by the vacuum expectation value of the BEH field.



The vacuum expectation value of the BEH field has a greater effect on massive particles.