UNIVERSITETET I BERGEN

ATLAS EXPERIMENT

The Higgs boson and a small tour of particle physics

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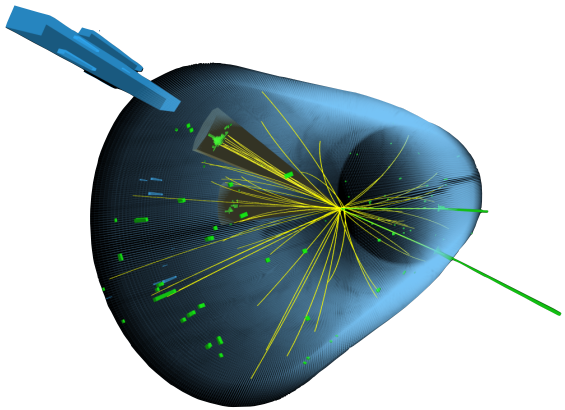
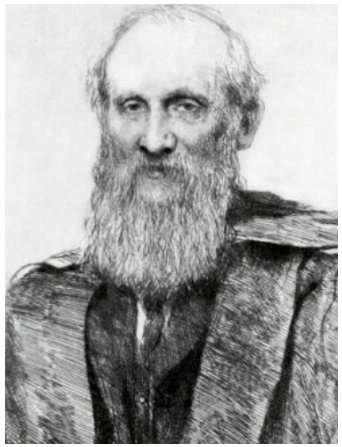
UiB Bachelor visit CERN 24.11.2023



Particle physics quick review

- In the early 1900s, most physicists believe that physics was complete, described by classical mechanics, thermodynamics and Maxwell's theory.

Address to the British association for the advancement of science

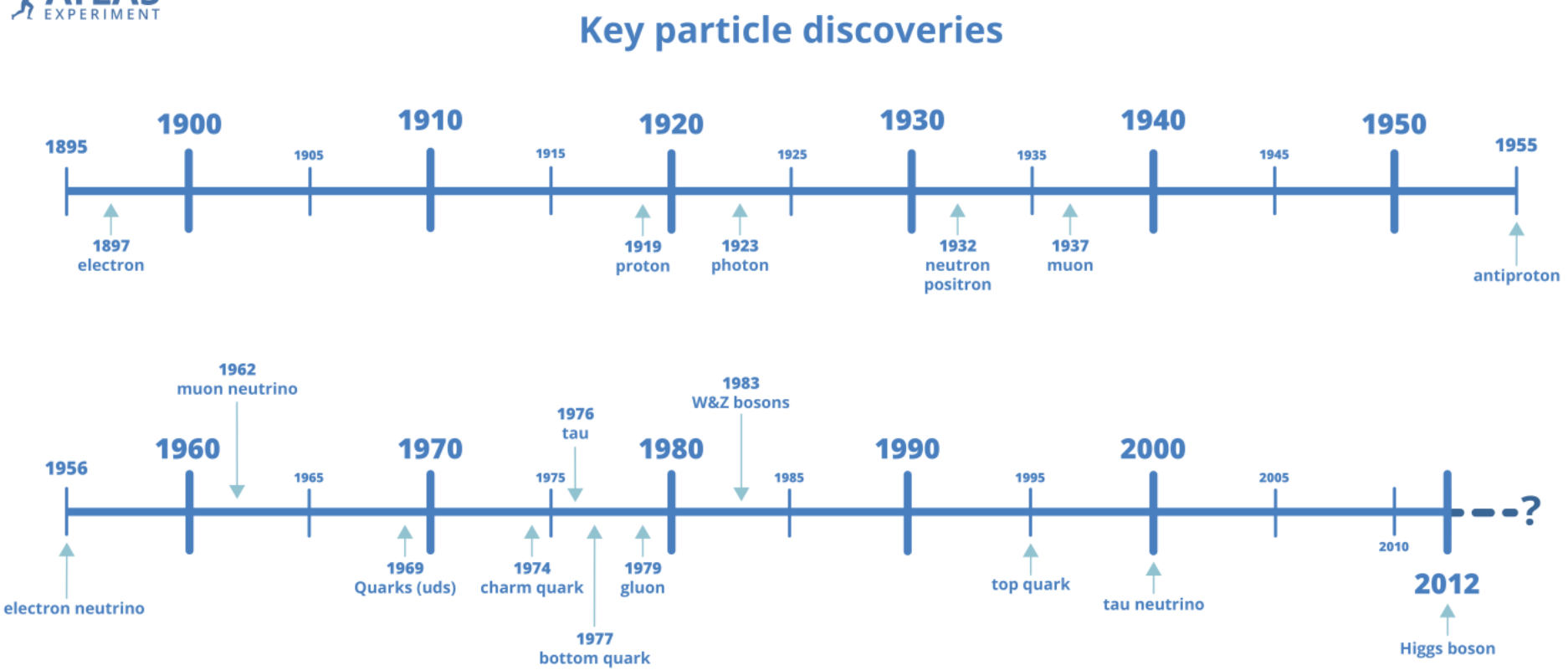


Lord Kelvin
1897

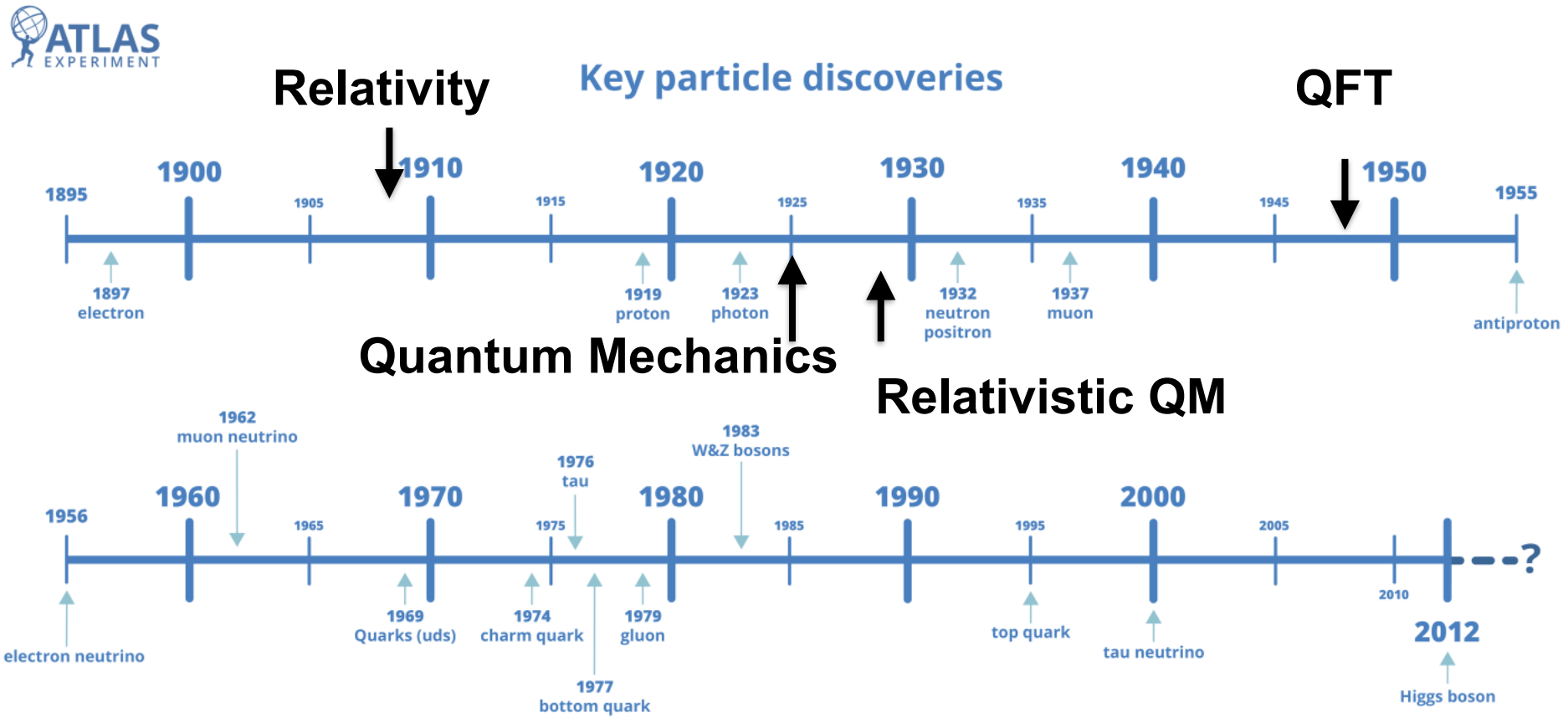
"There is nothing new to be discovered in physics now. All that remains are more and more precise measurements"

Well…

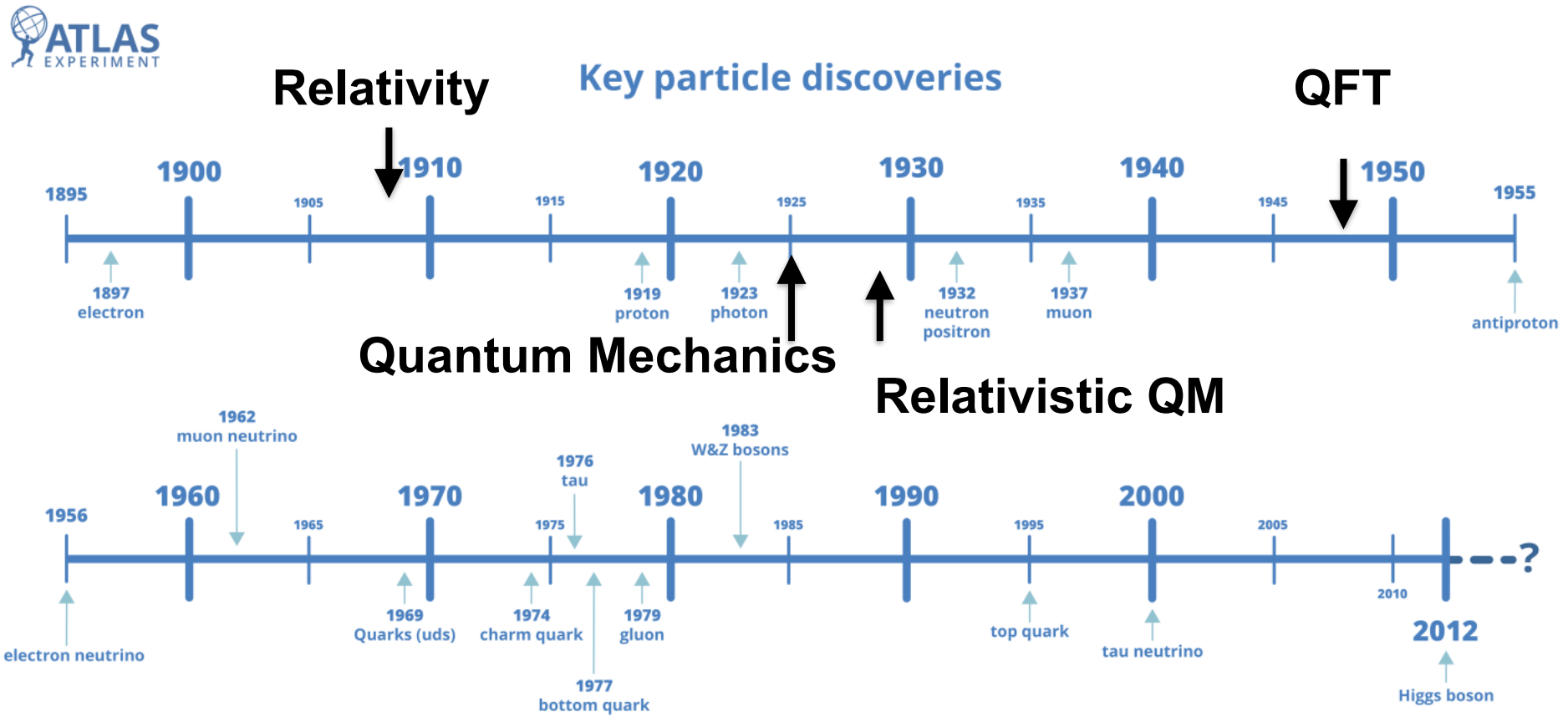
Particle physics quick review



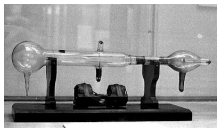
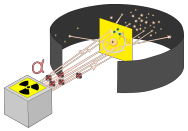
Particle physics quick review

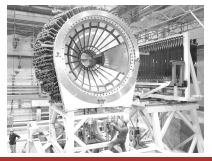
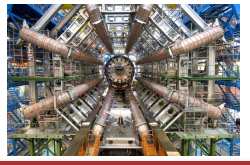


Particle physics quick review



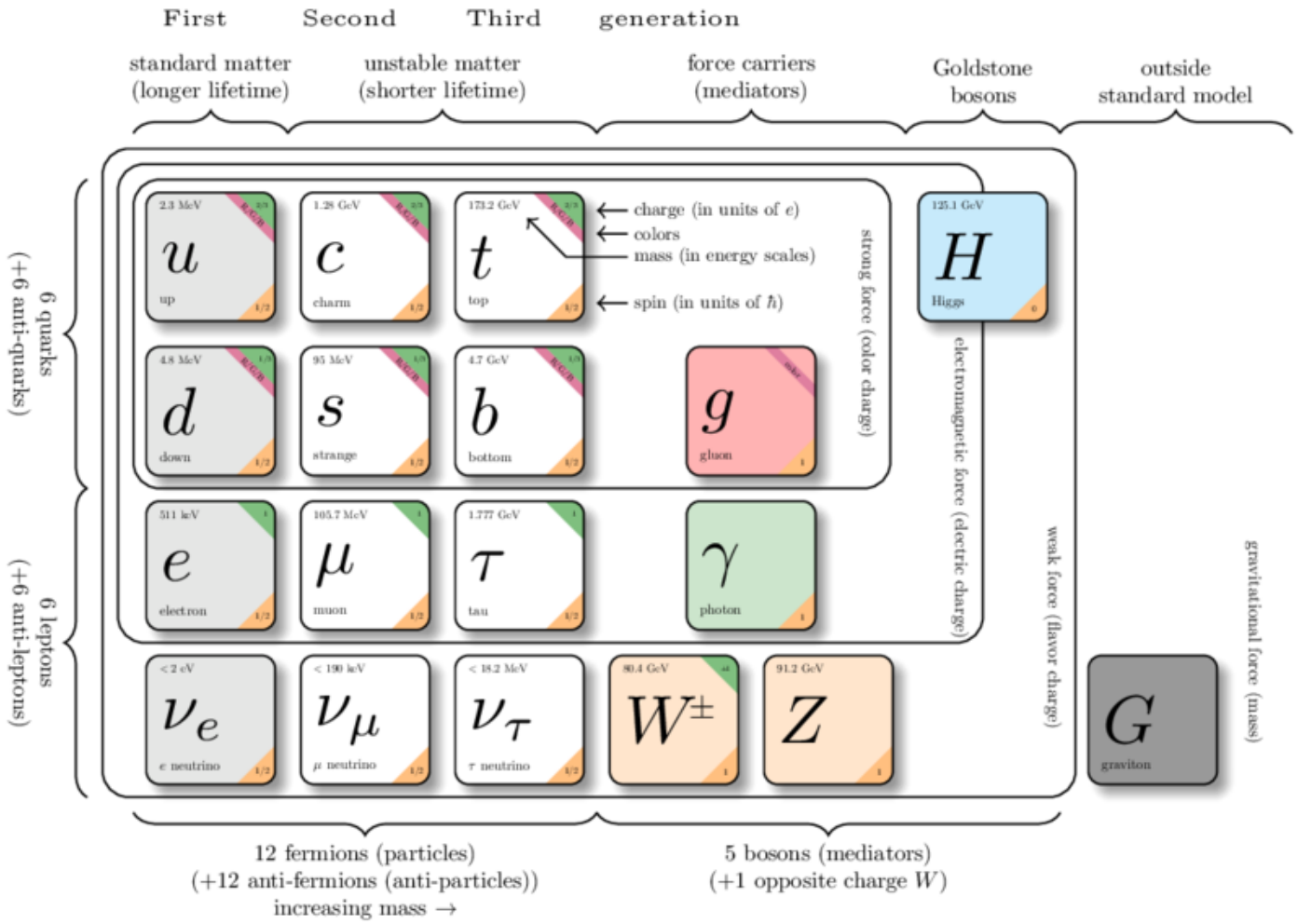
0.5 MeV 10 MeV 600 MeV 400 GeV 14 TeV

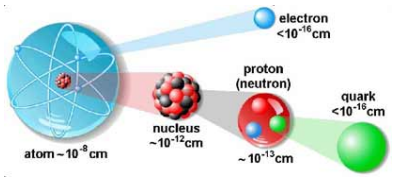




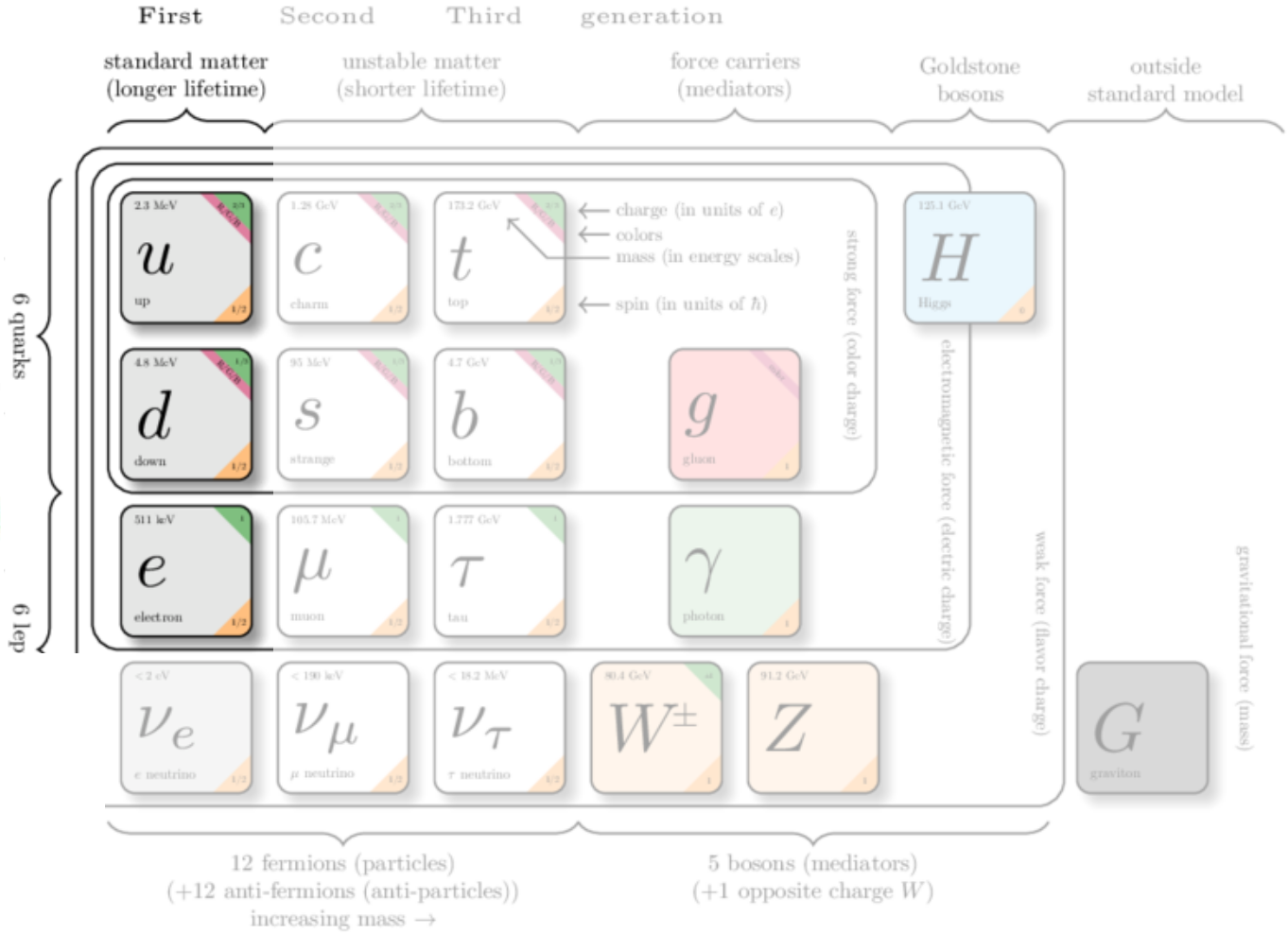
$$l \sim \frac{1}{E}$$

100 years of increasing energy



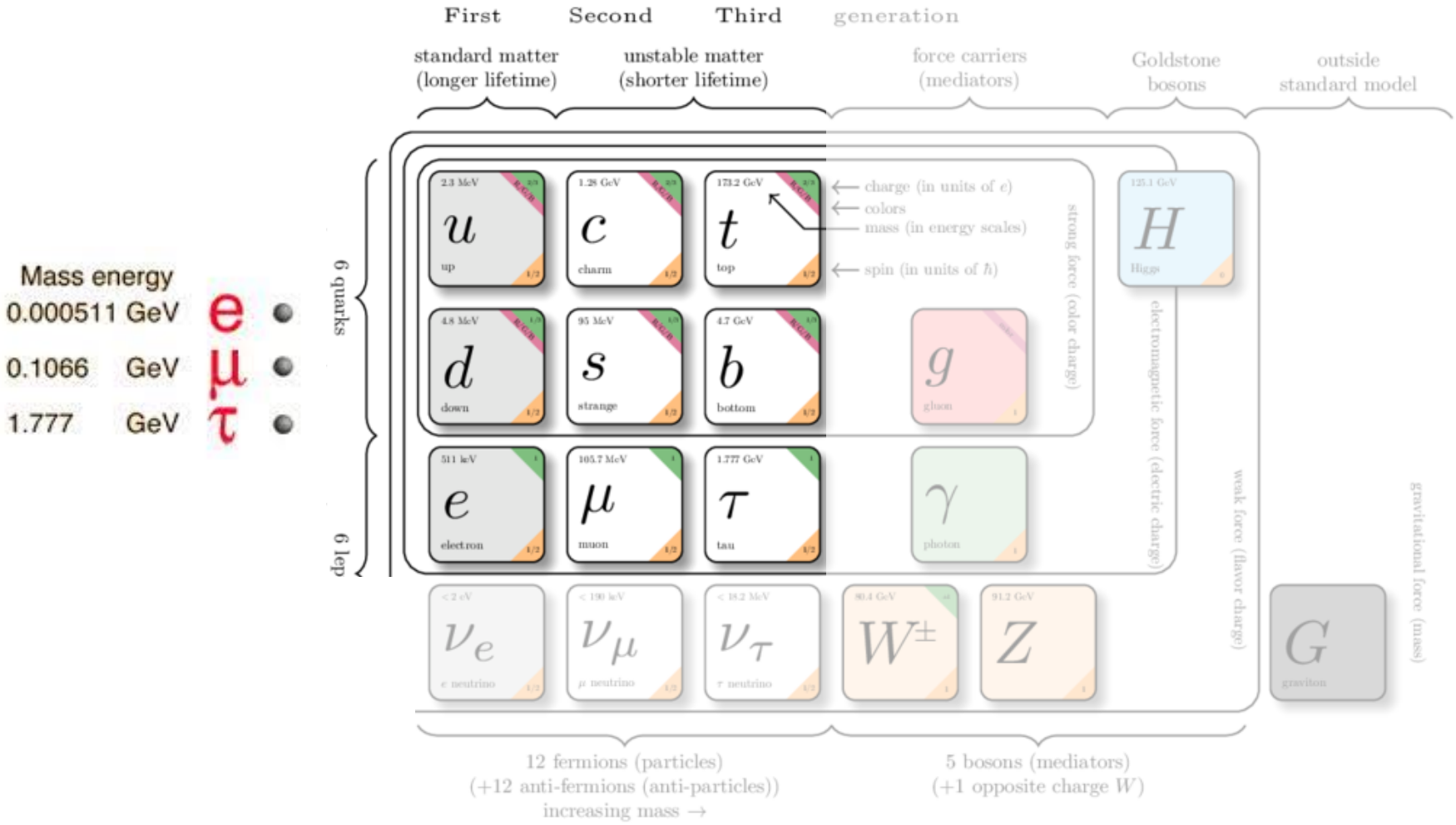
The standard model





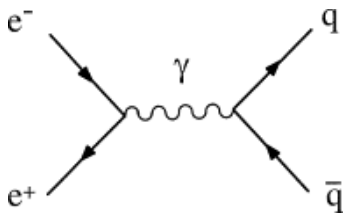
The standard model

Same particle types —> More massive



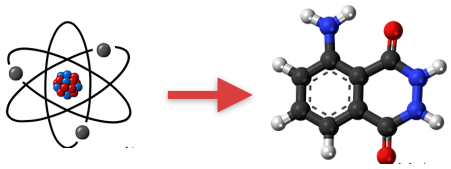
The standard model

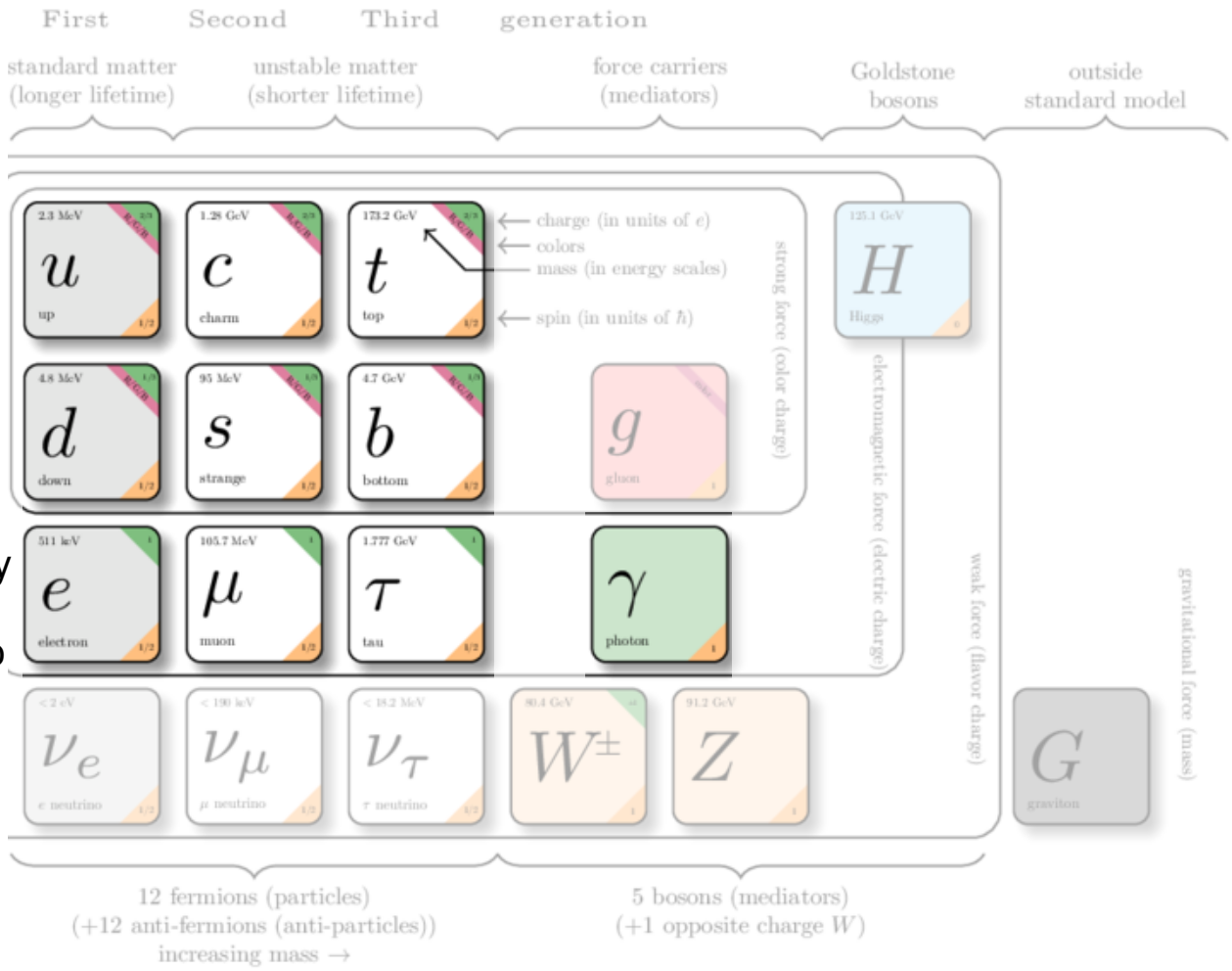
Electromagnetic interaction



Interacts with all electrically charges particles:

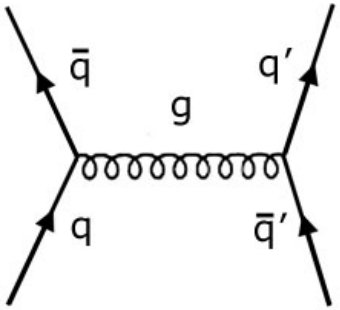
- Allows atoms to form into molecules





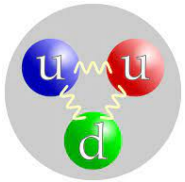
The standard model

Strong interaction

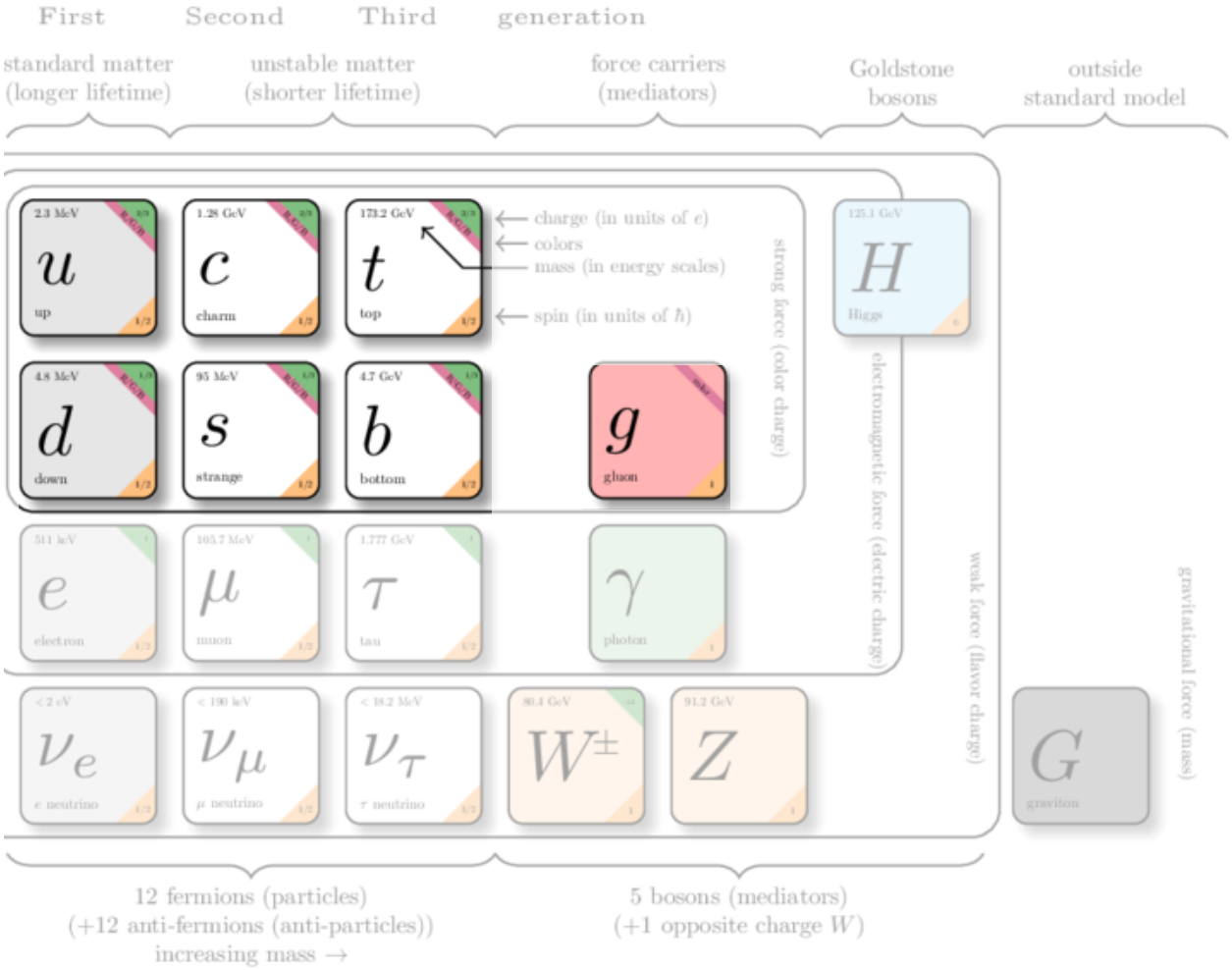


Interacts with color charge:

- Red
- Green
- Blue

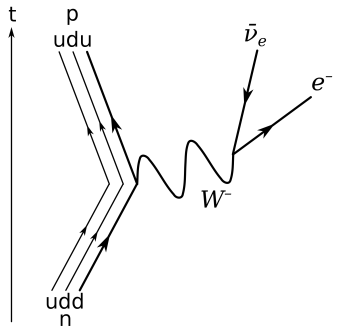


Allows quarks to form into protons and neutrons



The standard model

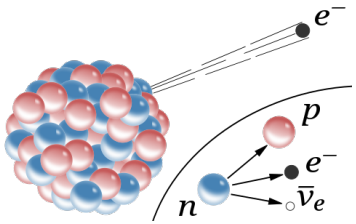
Weak interaction

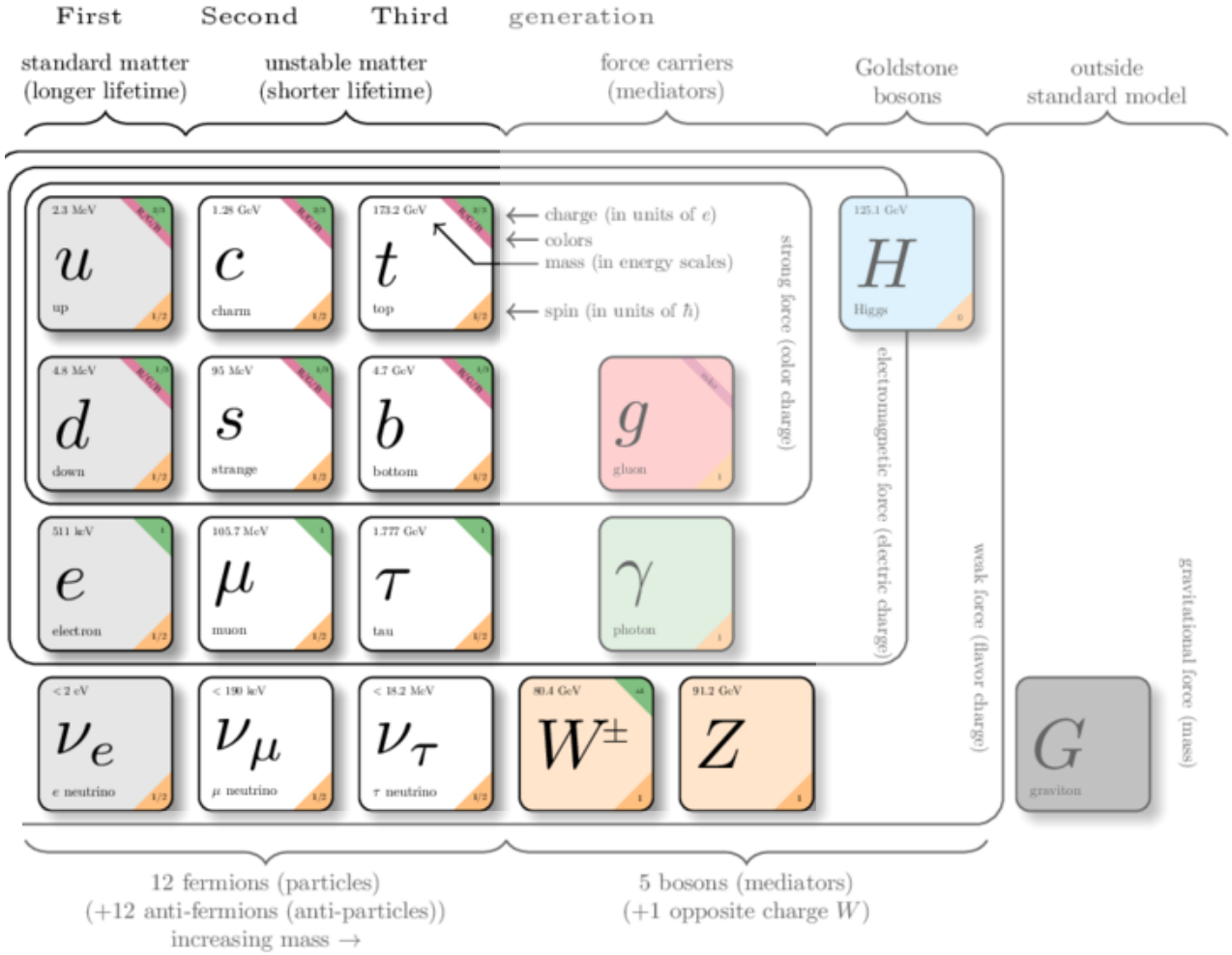


Changes flavour of particles:

- $p \rightarrow n$
- $\mu \rightarrow e$

Allows particle decays → Radioactivity

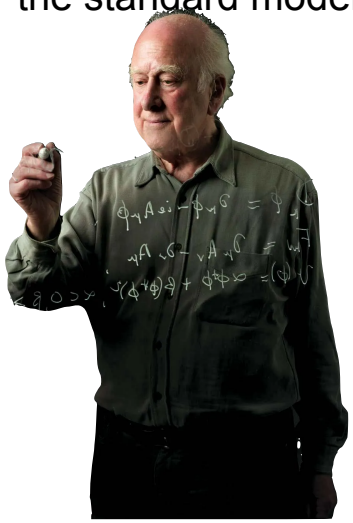


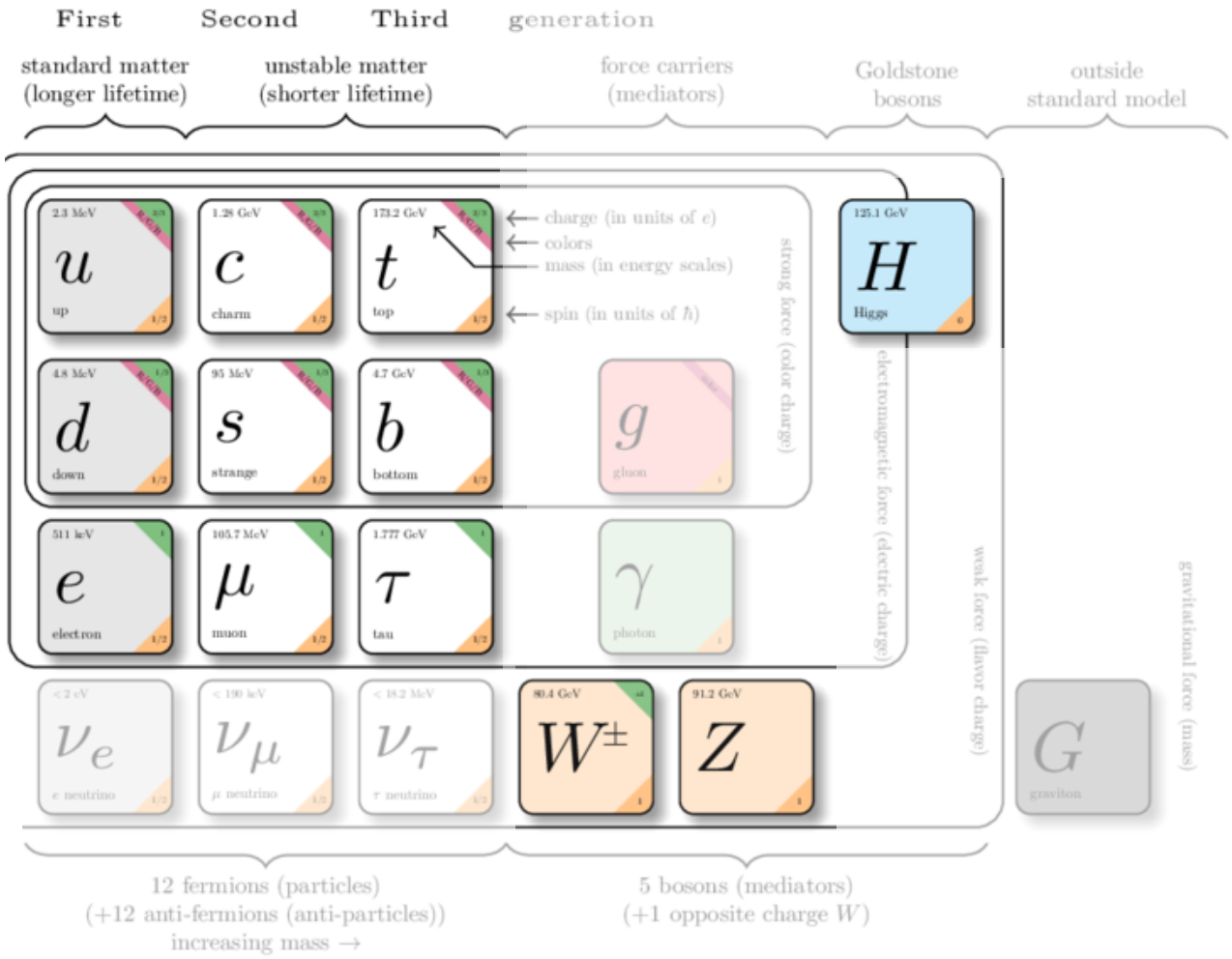


The standard model

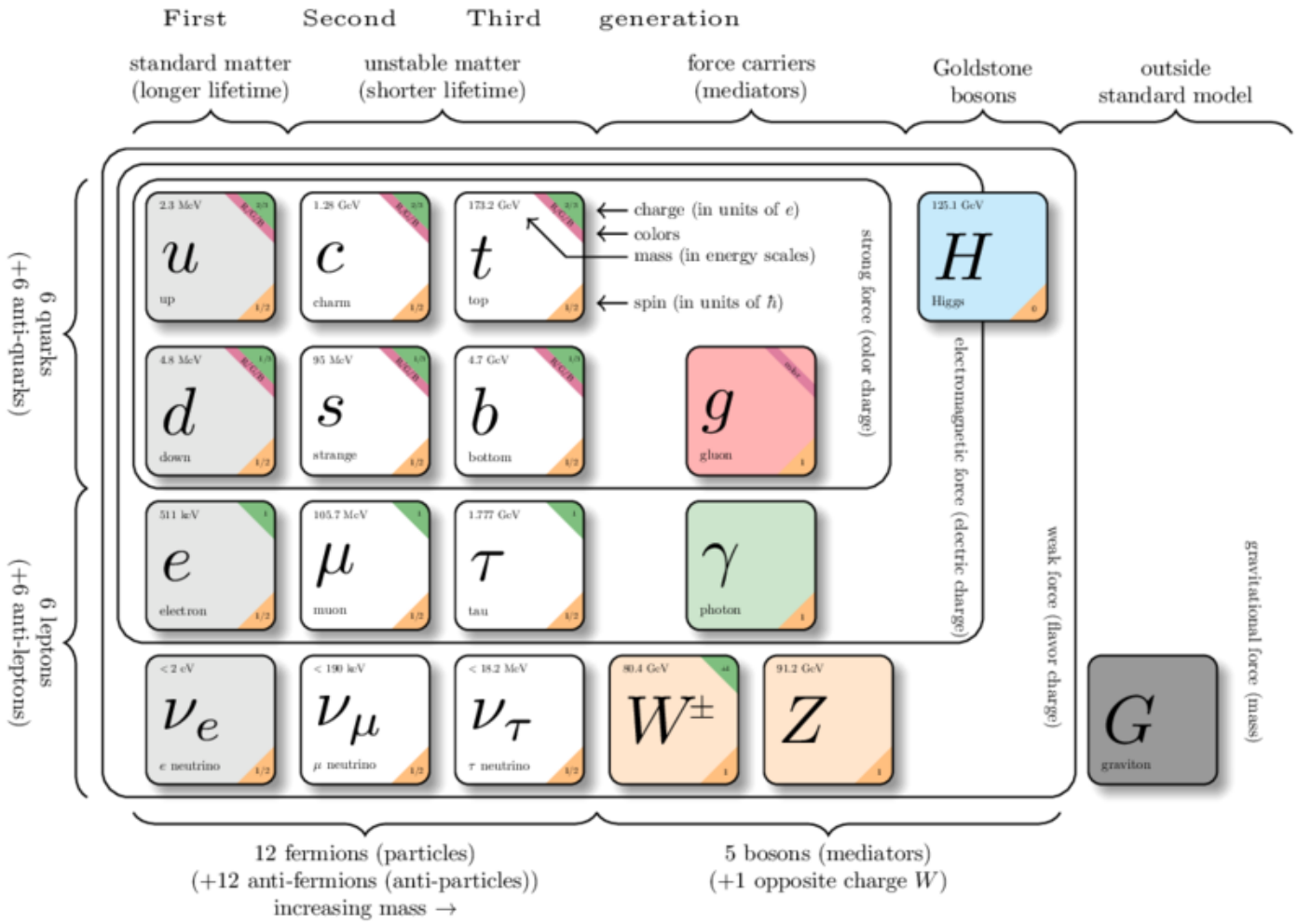
The Higgs boson

- Different than the other particles of the standard model
- Scalar spin 0
- Generates mass terms for all the massive particles in the standard model





But what is this thing?



Really an equation

$$
\begin{aligned}
\mathcal{L}_{SM} = & -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
& \tfrac{1}{2} i g_s^2 (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
& M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \\
& \tfrac{1}{2} m_h^2 H^2 - \partial_\mu \bar{\varepsilon}^+ \partial_\mu \bar{\varepsilon}^- - M^2 \bar{\varepsilon}^+ \bar{\varepsilon}^- - \tfrac{1}{2}\partial_\mu \bar{\varepsilon}^0 \partial_\mu \bar{\varepsilon}^0 - \tfrac{1}{2c_w^2} M \bar{\varepsilon}^0 \bar{\varepsilon}^0 - \beta_h [\tfrac{2M^2}{g^2} + \\
& \tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \bar{\varepsilon}^0 \bar{\varepsilon}^0 + 2\bar{\varepsilon}^+ \bar{\varepsilon}^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w [\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
& W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
& W^-_\nu \partial_\nu W^+_\mu)] - igs_w [\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - \\
& W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
& \tfrac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\nu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
& g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
& W^+_\nu W^-_\mu) - 2 A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha [H^3 + H\bar{\varepsilon}^0 \bar{\varepsilon}^0 + 2H\bar{\varepsilon}^+ \bar{\varepsilon}^-] - \\
& \tfrac{1}{8} g^2 \alpha_h [H^4 + (\bar{\varepsilon}^0)^4 + 4(\bar{\varepsilon}^+ \bar{\varepsilon}^-)^2 + 4(\bar{\varepsilon}^0)^2 \bar{\varepsilon}^+ \bar{\varepsilon}^- + 4H^2 \bar{\varepsilon}^+ \bar{\varepsilon}^- + 2(\bar{\varepsilon}^0)^2 H^2] - \\
& gMW^+_\mu W^-_\mu H - \tfrac{1}{2} g \tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \tfrac{1}{2} ig [W^+_\mu (\bar{\varepsilon}^0 \partial_\mu \bar{\varepsilon}^- - \bar{\varepsilon}^- \partial_\mu \bar{\varepsilon}^0) - \\
& W^-_\mu (\bar{\varepsilon}^0 \partial_\mu \bar{\varepsilon}^+ - \bar{\varepsilon}^+ \partial_\mu \bar{\varepsilon}^0)] + \tfrac{1}{2} g [W^+_\mu (H \partial_\mu \bar{\varepsilon}^- - \bar{\varepsilon}^- \partial_\mu H) - W^-_\mu (H \partial_\mu \bar{\varepsilon}^+ - \\
& \bar{\varepsilon}^+ \partial_\mu H)] + \tfrac{1}{2} g \tfrac{1}{c_w} (Z^0_\mu (H \partial_\mu \bar{\varepsilon}^0 - \bar{\varepsilon}^0 \partial_\mu H) - ig \tfrac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \bar{\varepsilon}^- - W^-_\mu \bar{\varepsilon}^+) + \\
& igs_w M A_\mu (W^+_\mu \bar{\varepsilon}^- - W^-_\mu \bar{\varepsilon}^+) - ig \tfrac{1-2c_w^2}{2c_w} Z^0_\mu (\bar{\varepsilon}^+ \partial_\mu \bar{\varepsilon}^- - \bar{\varepsilon}^- \partial_\mu \bar{\varepsilon}^+) + \\
& igs_w A_\mu (\bar{\varepsilon}^+ \partial_\mu \bar{\varepsilon}^- - \bar{\varepsilon}^- \partial_\mu \bar{\varepsilon}^+) - \tfrac{1}{4} g^2 W^+_\mu W^-_\mu [H^2 + (\bar{\varepsilon}^0)^2 + 2\bar{\varepsilon}^+ \bar{\varepsilon}^-] - \\
& \tfrac{1}{4} g^2 \tfrac{1}{c_w^2} Z^0_\mu Z^0_\mu [H^2 + (\bar{\varepsilon}^0)^2 + 2(2s_w^2 - 1)^2 \bar{\varepsilon}^+ \bar{\varepsilon}^-] - \tfrac{1}{2} g^2 \tfrac{s_w^2}{c_w} Z^0_\mu \bar{\varepsilon}^0 (W^+_\mu \bar{\varepsilon}^- + \\
& W^-_\mu \bar{\varepsilon}^+) - \tfrac{1}{2} ig^2 \tfrac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \bar{\varepsilon}^- - W^-_\mu \bar{\varepsilon}^+) + \tfrac{1}{2} g^2 s_w A_\mu \bar{\varepsilon}^0 (W^+_\mu \bar{\varepsilon}^- + \\
& W^-_\mu \bar{\varepsilon}^+) + \tfrac{1}{2} ig^2 s_w A_\mu H (W^+_\mu \bar{\varepsilon}^- - W^-_\mu \bar{\varepsilon}^+) - g^2 \tfrac{s_w}{c_w} (2c_w^2 - 1) Z^0_\mu A_\mu \bar{\varepsilon}^+ \bar{\varepsilon}^- - \\
& g^1 s_w^2 A_\mu A_\mu \bar{\varepsilon}^+ \bar{\varepsilon}^- - \bar{e}^\lambda (\gamma \partial + m^\lambda_e) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}^\lambda_j (\gamma \partial + m^\lambda_u) u^\lambda_j - \\
& \bar{d}^\lambda_j (\gamma \partial + m^\lambda_d) d^\lambda_j + igs_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j \gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j \gamma^\mu d^\lambda_j)] + \\
& \tfrac{ig}{4c_w} Z^0_\mu [(\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (\tfrac{4}{3} s_w^2 - \\
& 1 - \gamma^5) u^\lambda_j) + (\bar{d}^\lambda_j \gamma^\mu (1 - \tfrac{8}{3} s_w^2 - \gamma^5) d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} W^+_\mu [(\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) e^\lambda) + \\
& (\bar{u}^\lambda_j \gamma^\mu (1+\gamma^5) C_{\lambda\kappa} d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}} W^-_\mu [(\bar{e}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa} \gamma^\mu (1 + \\
& \gamma^5) u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} \tfrac{m^\lambda_e}{M} [-\bar{\varepsilon}^+ (\bar{\nu}^\lambda (1-\gamma^5) e^\lambda) + \bar{\varepsilon}^- (\bar{e}^\lambda (1+\gamma^5) \nu^\lambda)] - \\
& \tfrac{g}{2} \tfrac{m^\lambda_e}{M} [H (\bar{e}^\lambda e^\lambda) + i\bar{\varepsilon}^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}} \bar{\varepsilon}^+ [-m^\kappa_d (\bar{u}^\lambda_j C_{\lambda\kappa} (1-\gamma^5) d^\kappa_j) + \\
& m^\lambda_u (\bar{u}^\lambda_j C_{\lambda\kappa} (1+\gamma^5) d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}} \bar{\varepsilon}^- [m^\lambda_d (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1+\gamma^5) u^\kappa_j) - m^\kappa_u (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 - \\
& \gamma^5) u^\kappa_j] - \tfrac{g}{2} \tfrac{m^\lambda_u}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2} \tfrac{m^\lambda_d}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2} \tfrac{m^\lambda_u}{M} \bar{\varepsilon}^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \\
& \tfrac{ig}{2} \tfrac{m^\lambda_d}{M} \bar{\varepsilon}^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \\
& \tfrac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + igs_w W^+_\mu (\partial_\mu \bar{Y} X^- - \\
& \partial_\mu \bar{X}^+ Y) + igc_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + igs_w W^-_\mu (\partial_\mu \bar{X}^- Y - \\
& \partial_\mu \bar{Y} X^+) + igc_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
& \partial_\mu \bar{X}^- X^-) - \tfrac{1}{2} gM [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2} \bar{X}^0 X^0 H] + \\
& \tfrac{1-2c_w^2}{2c_w} igM [\bar{X}^+ X^0 \bar{\varepsilon}^+ - \bar{X}^- X^0 \bar{\varepsilon}^-] + \tfrac{1}{2c_w} igM [\bar{X}^0 X^- \bar{\varepsilon}^+ - \bar{X}^0 X^+ \bar{\varepsilon}^-] + \\
& igMs_w [\bar{X}^0 X^- \bar{\varepsilon}^+ - \bar{X}^0 X^+ \bar{\varepsilon}^-] + \tfrac{1}{2} igM [\bar{X}^+ X^+ \bar{\varepsilon}^0 - \bar{X}^- X^- \bar{\varepsilon}^0]
\end{aligned}
$$

Really an equation

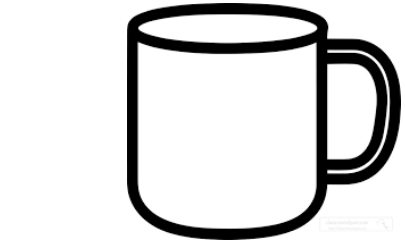
$$\mathcal{L}_{SM} = -\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w [\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - igs_w [\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\nu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \frac{1}{8}g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2}g[W^+_\mu (H\partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H\partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu (H\partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig\frac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + igs_w M A_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) - ig\frac{1-2c_w^2}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \frac{1}{4}g^2 \frac{1}{c_w^2} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \frac{s_w}{c_w}(2c_w^2 - 1) Z^0_\mu A_\mu \phi^+ \phi^- - g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma\partial + m^\lambda_e) e^\lambda - \bar{\nu}^\lambda \gamma\partial \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + m^\lambda_u) u^\lambda_j - \bar{d}^\lambda_j (\gamma\partial + m^\lambda_d) d^\lambda_j + igs_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j \gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j \gamma^\mu d^\lambda_j)] + \frac{ig}{4c_w} Z^0_\mu [(\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (\frac{4}{3}s_w^2 - 1 - \gamma^5) u^\lambda_j) + (\bar{d}^\lambda_j \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d^\lambda_j)] + \frac{ig}{2\sqrt{2}} W^+_\mu [(\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (1+\gamma^5) C_{\lambda\kappa} d^\kappa_j)] + \frac{ig}{2\sqrt{2}} W^-_\mu [(\bar{e}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa} \gamma^\mu (1+\gamma^5) u^\lambda_j)] + \frac{ig}{2\sqrt{2}} \frac{m^\lambda_e}{M} [-\phi^+ (\bar{\nu}^\lambda (1-\gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1+\gamma^5) \nu^\lambda)] - \frac{g}{2}\frac{m^\lambda_e}{M} [H(\bar{e}^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m^\kappa_d (\bar{u}^\lambda_j C_{\lambda\kappa} (1-\gamma^5) d^\kappa_j) + m^\lambda_u (\bar{u}^\lambda_j C_{\lambda\kappa} (1+\gamma^5) d^\kappa_j)] + \frac{ig}{2M\sqrt{2}} \phi^- [m^\lambda_d (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1+\gamma^5) u^\kappa_j) - m^\kappa_u (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1-\gamma^5) u^\kappa_j)] - \frac{g}{2}\frac{m^\lambda_u}{M} H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m^\lambda_d}{M} H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m^\lambda_d}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + igs_w W^+_\mu (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + igc_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + igs_w W^-_\mu (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} igM[\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} igM[\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + igMs_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2} igM[\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]$$

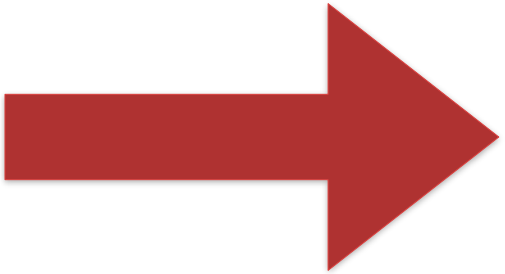
Not so nice looking..

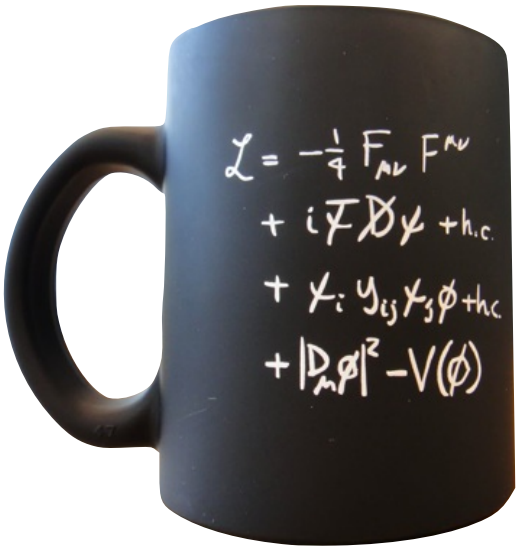
Let's simplify

$$\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \tfrac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\nu W^-_\mu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}\tfrac{m^\lambda_e}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \tfrac{g}{2}\tfrac{m^\lambda_e}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) - \tfrac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H] + \tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]$$

Apply the coffee mug Transformation



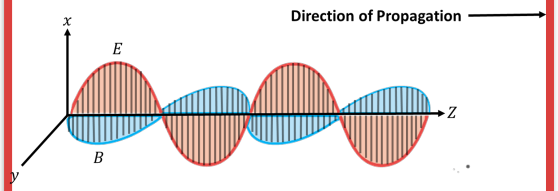




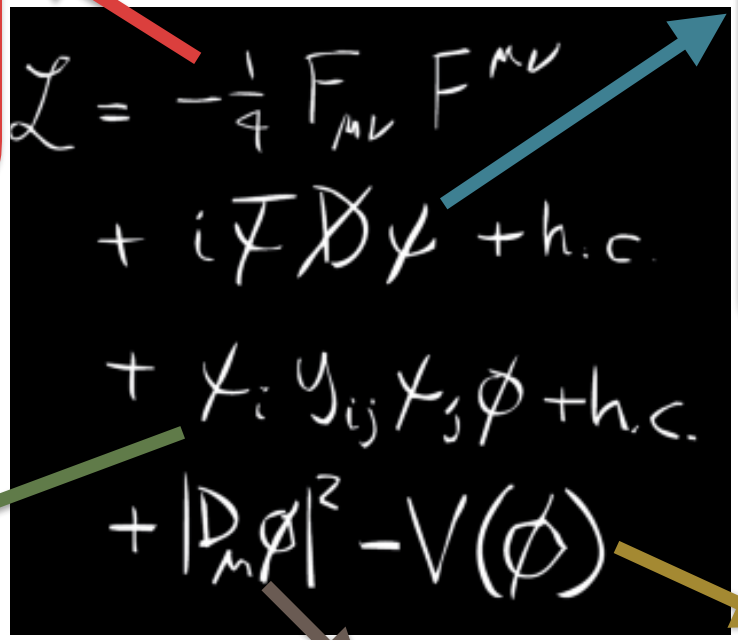
Coffee mug in nature

Kinetic terms for gauge bosons (Propagating free fields)

$$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$$

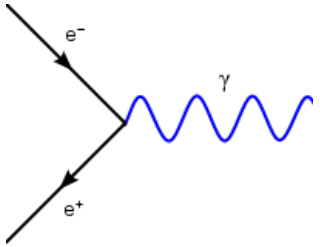


Want to learn this?
Phys203 and Phys342



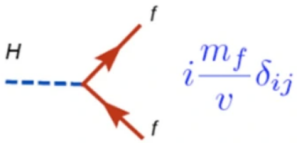
Interactions between Gauge bosons and fermions
Example QED:

$$\bar{\psi}(i\gamma^\mu D_\mu)\psi$$
$$D_\mu = \partial_\mu + ieQA_\mu$$

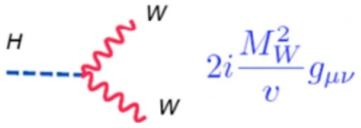


Yukawa interactions between Higgs (ϕ) and fermions ψ (Fermion masses)

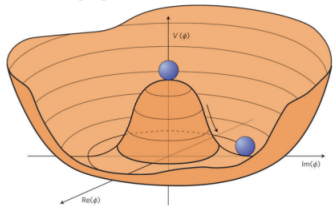
$$m_i(\bar{\psi}_i\psi_i) + \frac{m_i}{\nu}\phi(\bar{\psi}_i\psi_i)$$



Higgs covariant term (Z and W masses)



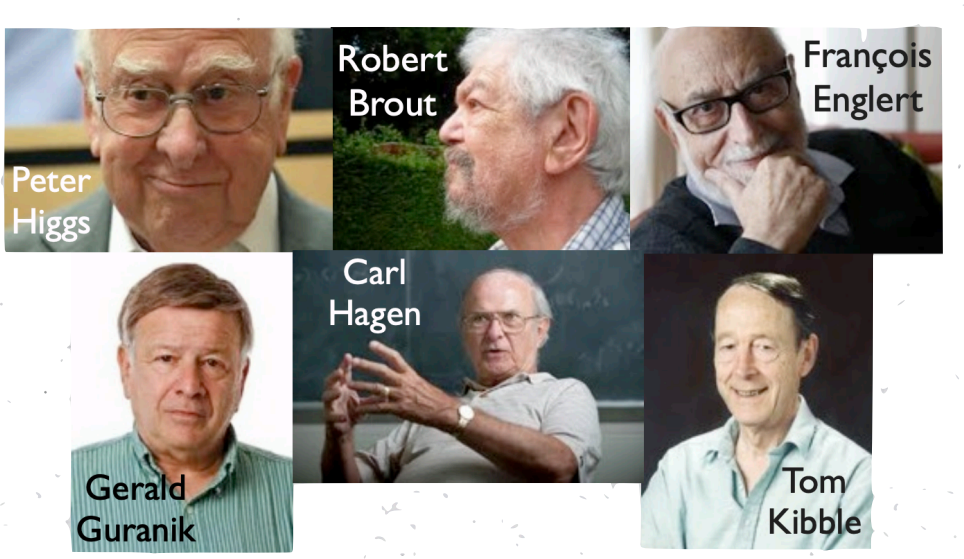
Higgs potential



Why did we need the Higgs?

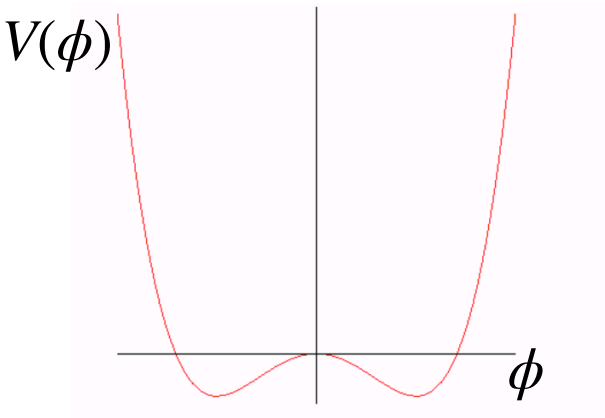
- One can't just add mass terms naively in the standard model —> Leads to problems with symmetry:
  - **Chiral fermions must be massless**
  - **Z and W must be massless due to transformation properties**
- Yet we know and have measured particles to have mass

Enter the Higgs Mechanism!



Higgs potential

- Introduce a new field to nature: ϕ



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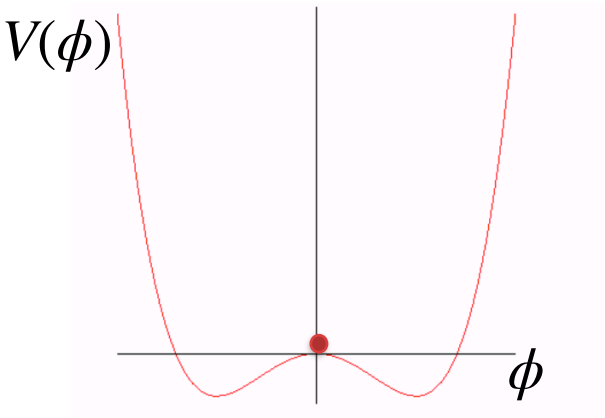
Higgs potential

- Introduce a new field to nature: ϕ

- **Lowest energy state at $\phi = 0$:**
  - Rotational symmetric
  - Vacuum = zero particles
  - Nothing interacts $\rightarrow$ no mass
  - Very unstable: Potential not at its lowest



Higgs potential

- Introduce a new field to nature: ϕ

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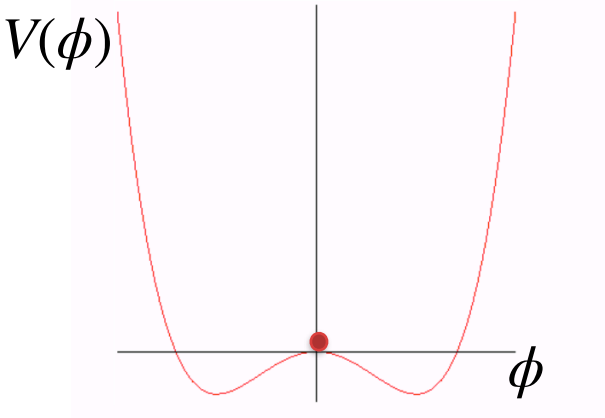
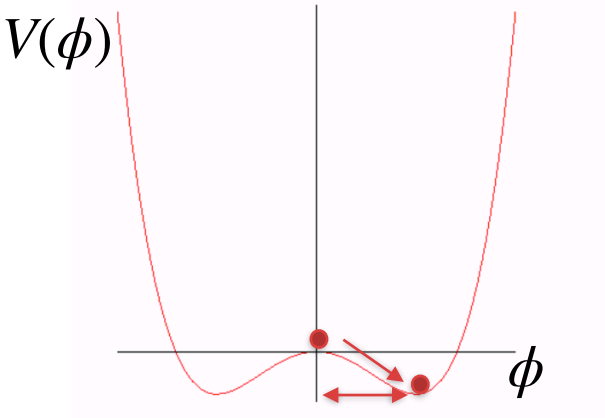
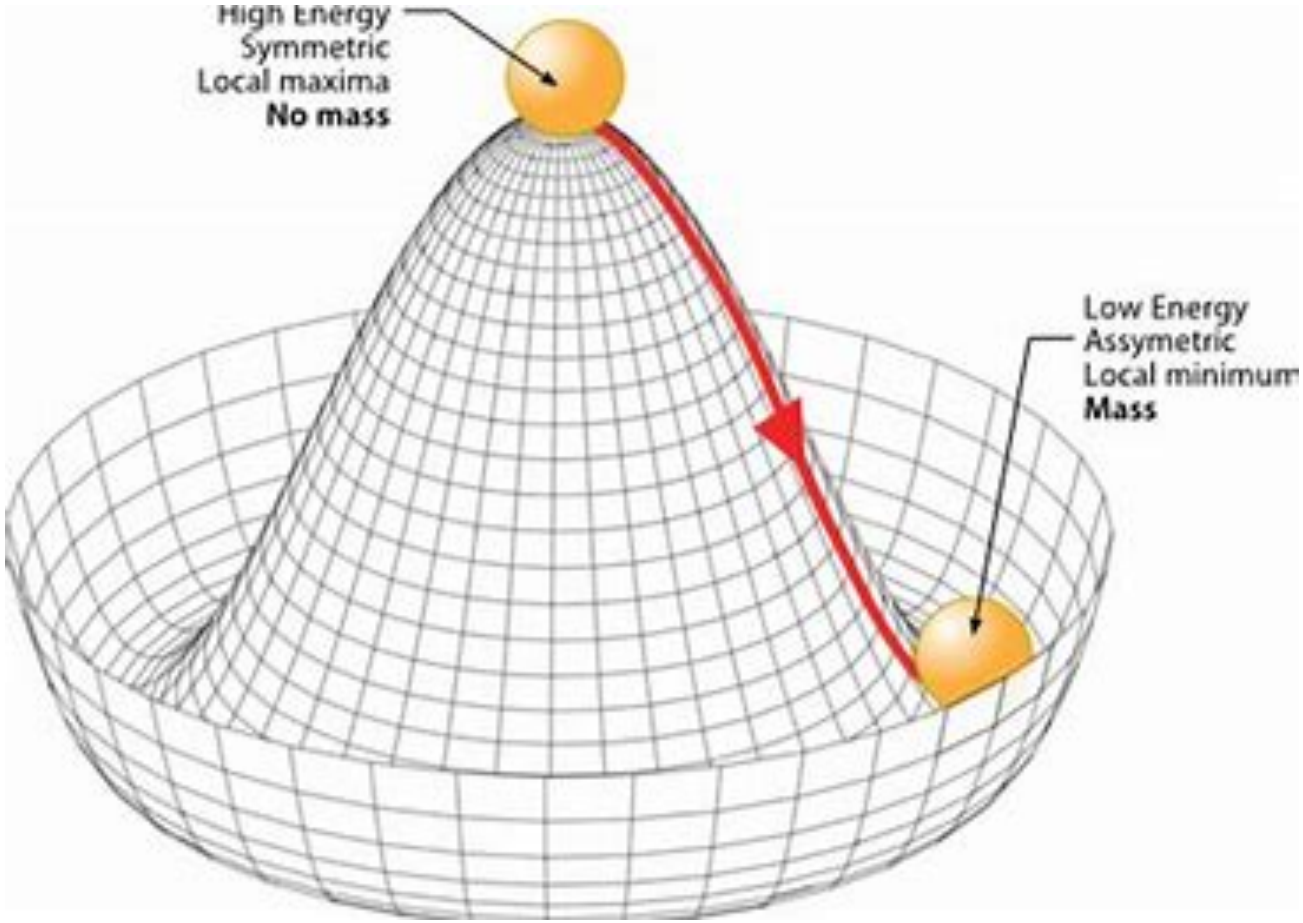


- **Lowest energy state at $\phi \neq 0$:**
  - The field ϕ "decays" into a new minimum
  - Breaks the rotational symmetry: Spontaneous symmetry breaking
  - Vacuum is not the zero particle state since $\phi \neq 0$.
  - What does that mean? **Vacuum has energy!**



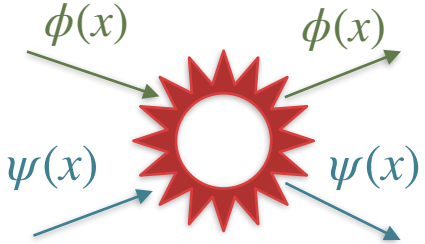
Spontaneous symmetry breaking

- “The Mexican hat potential”

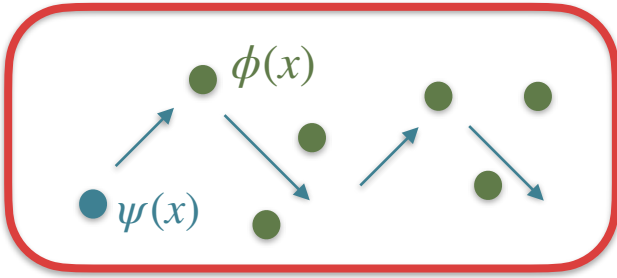


Generating mass

- Imagine this Higgs field ϕ now interacts with some other field ψ

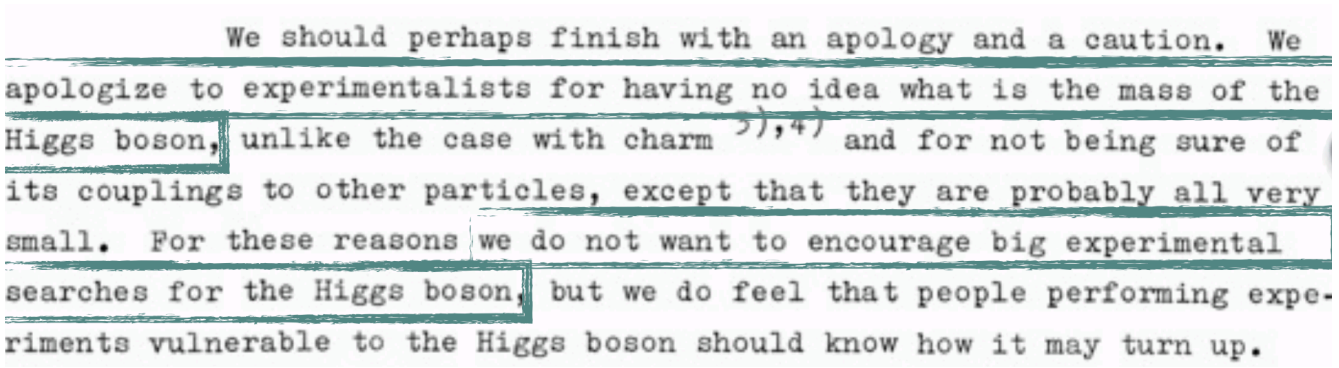


- After symmetry breaking the lowest energy vacuum state of ϕ has **energy** (non-zero vacuum expectation value)
- Energy —> Particles: Can visualise particle ψ moving through space bumping into ϕ particles
- This slows down ψ, and can be interpreted as mass
- Mass is proportional to Higgs coupling:
  - Photon: $m_\gamma = 0$ GeV (No Higgs coupling)
  - Electron: $m_e = 500$ MeV (Small Higgs coupling)
  - Top quark: $m_t = 170$ GeV (Very large Higgs coupling)



How was it found? A 50 year quest

- Predicted in 60s by Peter Higgs and independently by a team by François Englert and Robert Brout
- Predicting it was one thing, but actually finding was another:
  - Decays instantaneously, very tiny window to observe it
  - Mass of the particle could be anywhere from 10 - 1000 GeV
  - For decades the search was considered impossible



We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3),4)] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

A phenomenological profile of the Higgs boson; Ellis, Gaillard, Nanopoulos; 1975

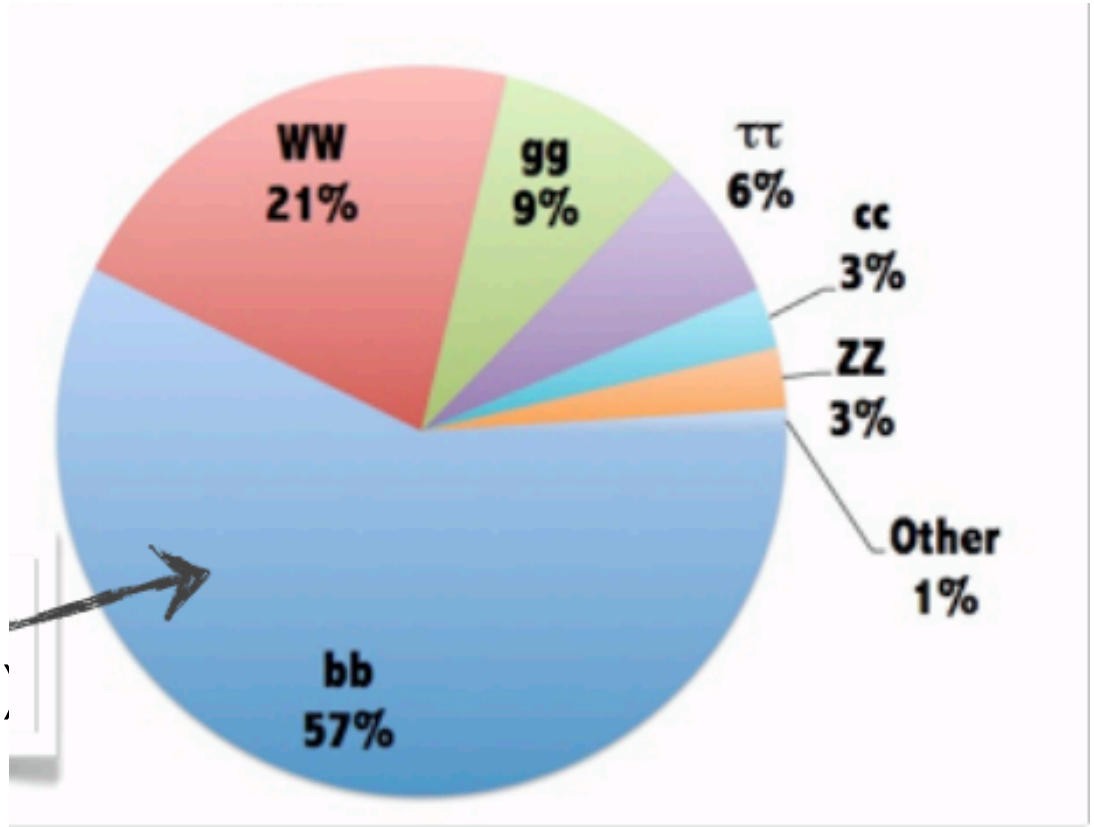
How was it found? A 50 year quest

- Very unstable, can only be seen from decay products
- Couplings proportional to mass:

Most visible:

$$H \to WW$$
$$H \to ZZ$$
$$H \to \gamma\gamma$$

Hard to see:
(Lots of background)



How was it found? A 50 year quest

- Technology somewhat caught up in 80s with bigger particle colliders.
- Still evaded detection for a few decades
- Each null result narrowed the possible mass range
- Early days of the LHC: Mass window narrowed down to 115-130 GeV
- Very low probability for production: One Higgs per 10 billon collision!
- Need lots of Data!

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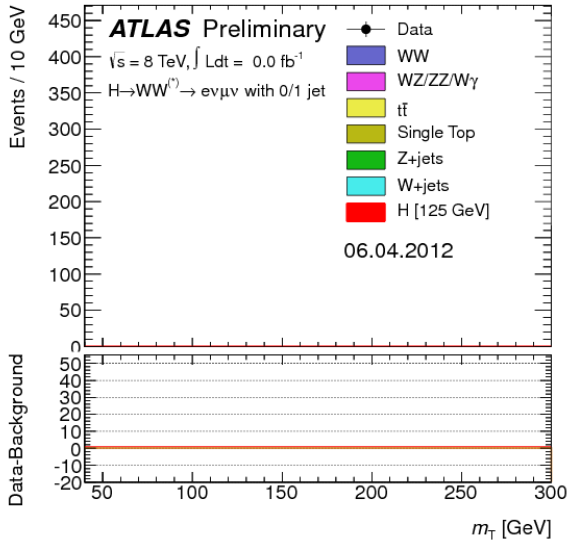
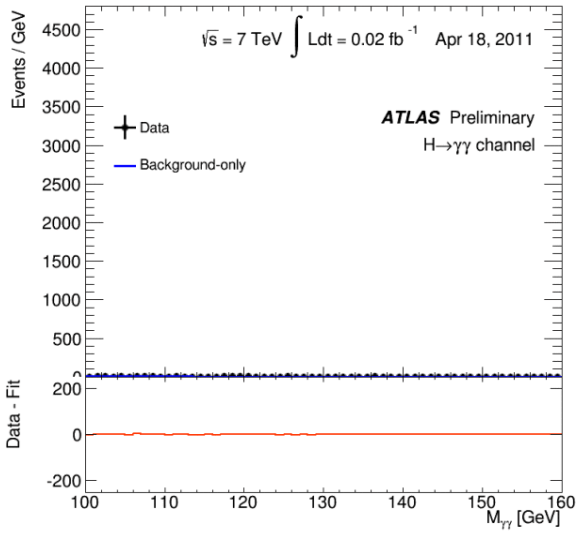
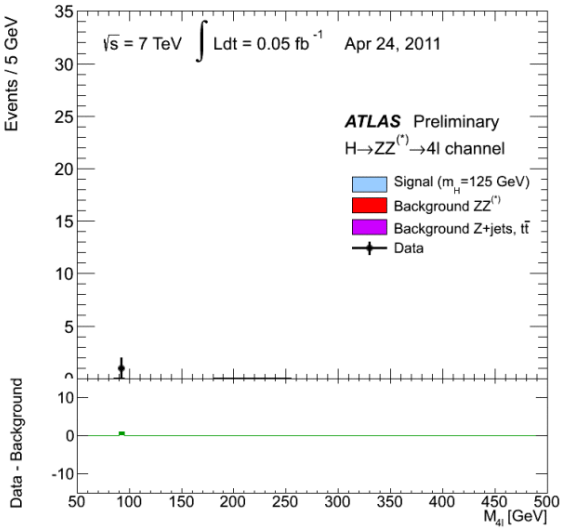
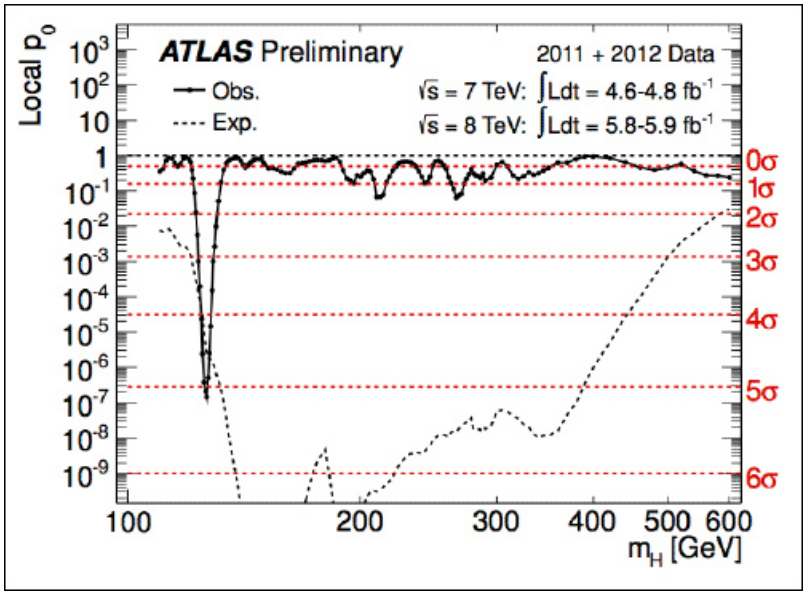






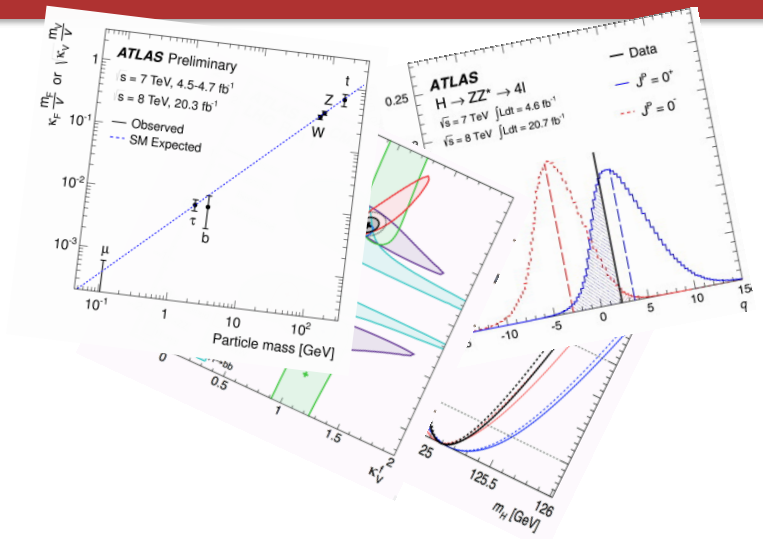
Discovery

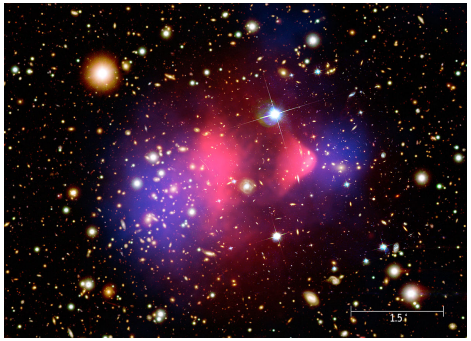
- In July 2012 the ATLAS and CMS experiments at CERN announced that they **independently** observed a new particle
- Mass 125 GeV and consistent with the Higgs boson!

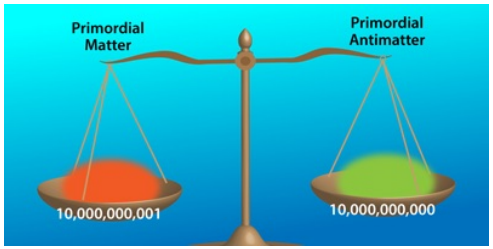


Where to now?

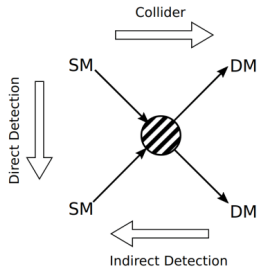
- Since discovery we have a lot more data!
- Everything points the Higgs being consistent with the standard model
- **Still many unanswered questions!**
  - What explain the Higgs mass at 125 GeV?
  - More Higgs bosons?
  - What explains the particle mass pattern?
  - **Connections to Dark Matter?**
  - **Where is all the antimatter in the universe?**







My work!



Try for yourself!

- Every year CERN and other particle physics laboratories in Europe hosts summer student programs for bachelor and master students
- Great opportunity to take part in the experiments at CERN and meet people in the field:

  - CERN summer student program 2024 (Deadline 30.01.2024):
    - https://www.smartrecruiters.com/CERN/74399941597816-cern-summer-student-programme-2024-member-and-non-member-state-
  - DESY summer student programme 2024 (Hamburg):
    - https://summerstudents.desy.de/e177241/index_eng.html?preview=preview

That's all!