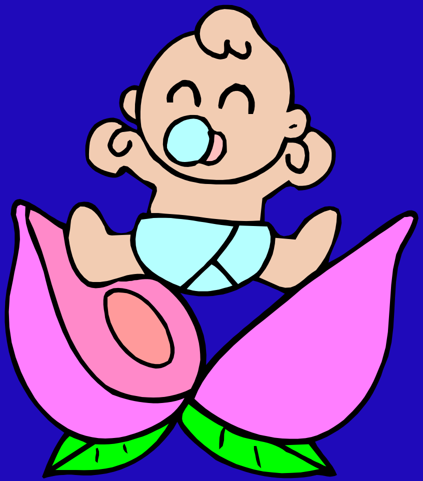
Particle Physics
The Standard Model

Antonio Pich

IFIC, CSIC – Univ. Valencia

Antonio.Pich@cern.ch

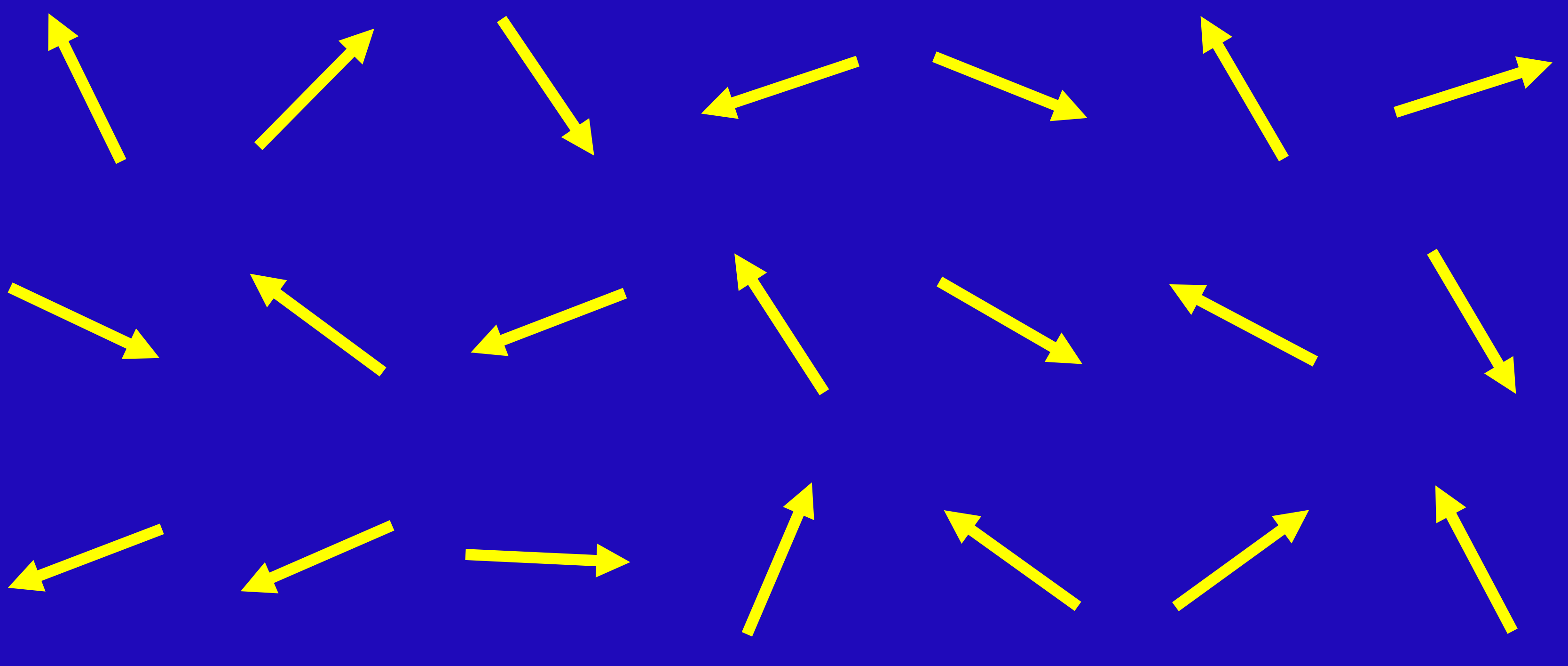
6. Symmetry Breaking



- Spontaneous Symmetry Breaking
- Scalar Potential
- Ground State Symmetry
- Higgs Mechanism
- The Higgs Boson
- Fermion Masses

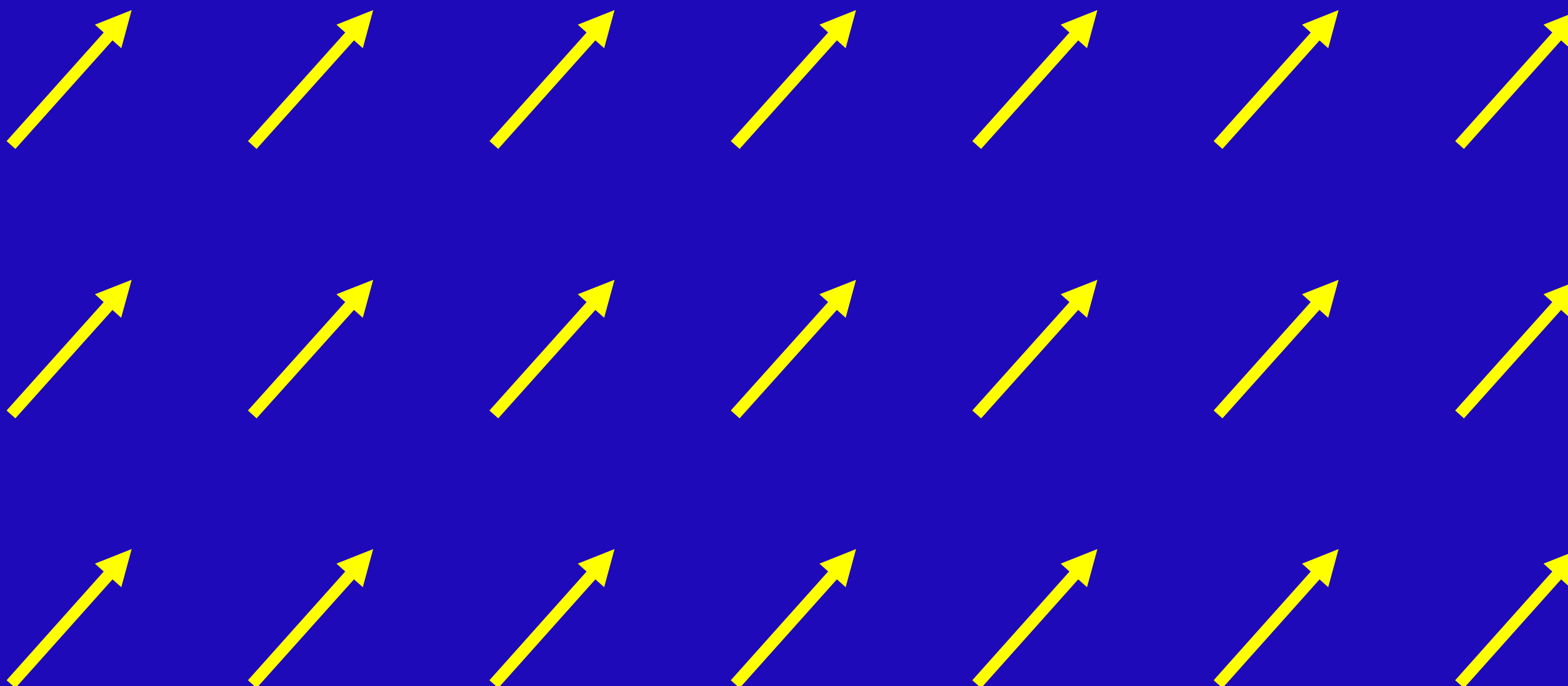
FERROMAGNET

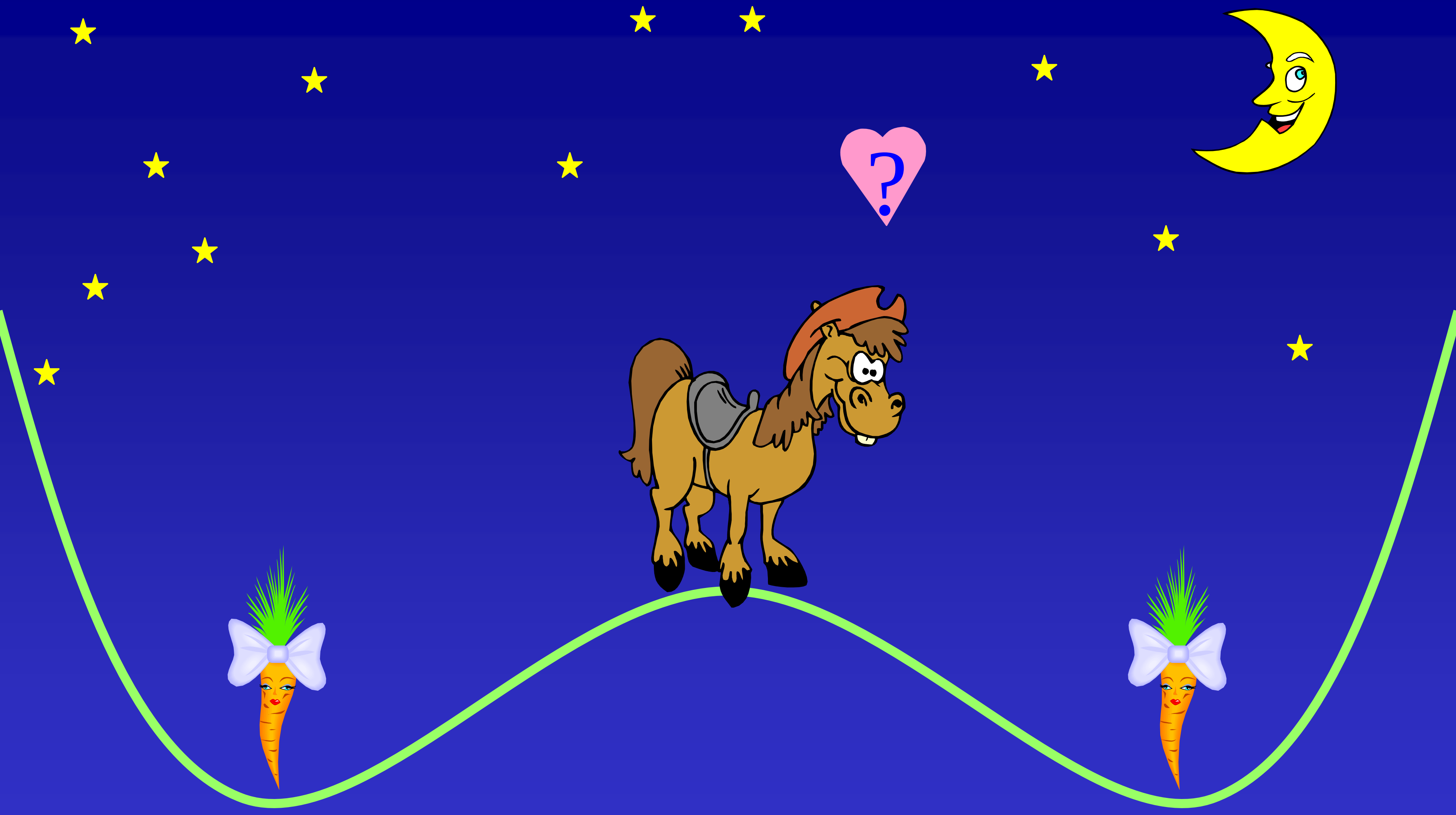
$T > T_C$

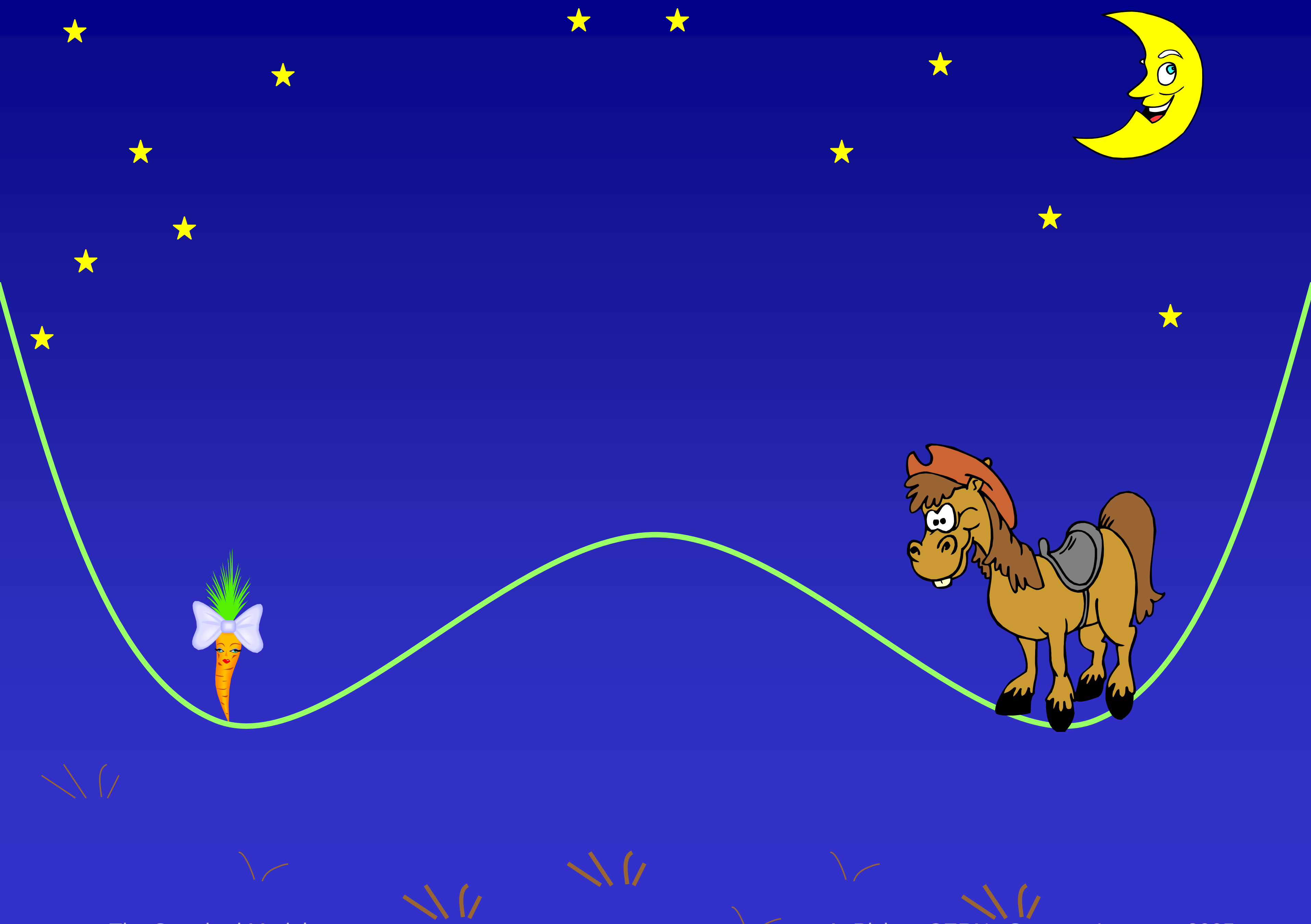


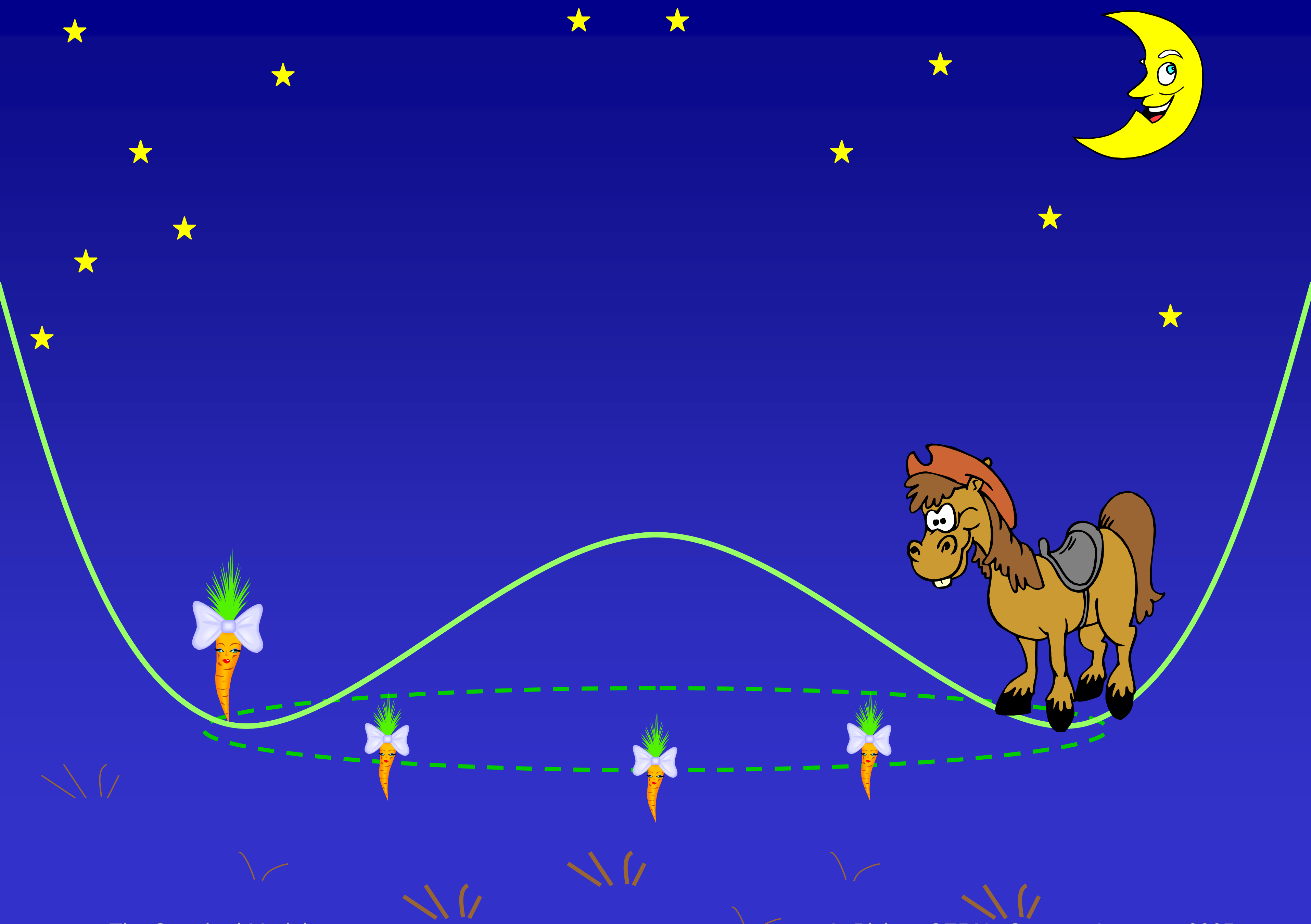
FERROMAGNET

$T < T_C$









SCALAR POTENCIAL

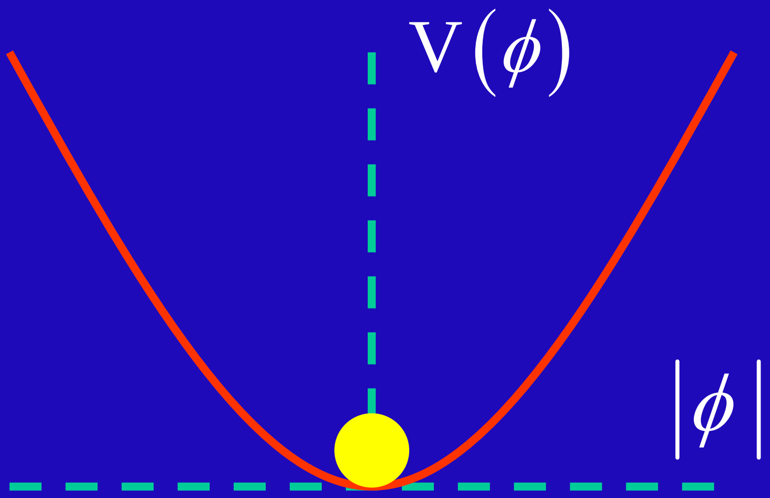
$$\mathcal{L}(\phi) = \partial_\mu \phi^\dagger \partial^\mu \phi - V(\phi)$$

$$\mathrm{V}(\phi) = \mu^2 \phi^\dagger \phi + h (\phi^\dagger \phi)^2$$

Phase Symmetry: $\phi(x) \to \mathrm{e}^{i\theta} \phi(x)$

$h > 0 \quad ; \quad \mu^2 > 0$

$M_\phi = \mu$



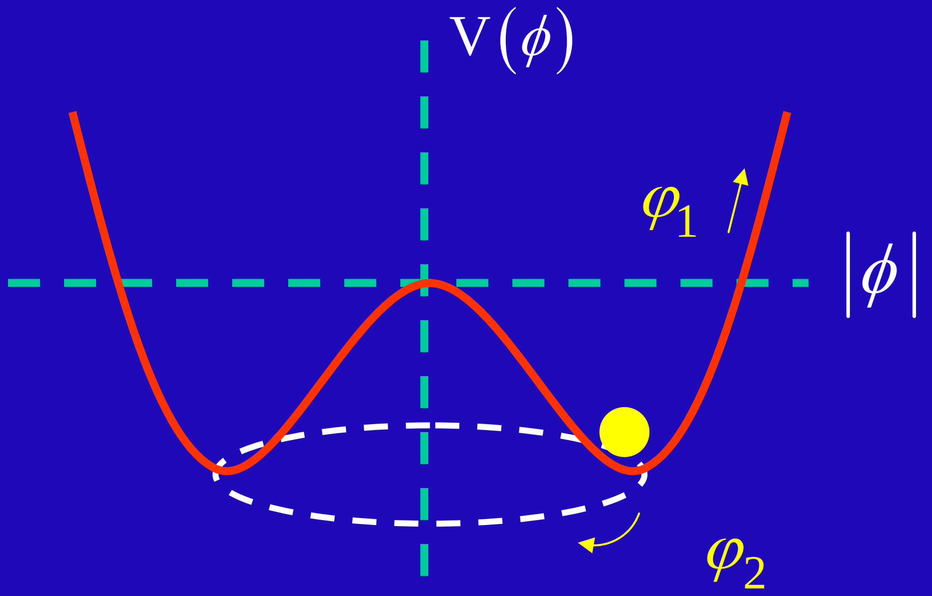
Trivial Minimum **(Ground State / Vacuum):** $\phi = \phi_0 = 0$

$$V(\phi) = \mu^2\, \phi^\dagger \phi + h\, (\phi^\dagger \phi)^2$$

Phase Symmetry:

$$\phi(x) \to e^{i\theta}\, \phi(x)$$

$$\mu^2 < 0$$



Degenerate Minima

(Ground State / Vacuum)

$$|\phi_0| = \sqrt{\frac{-\mu^2}{2h}} \equiv \frac{v}{\sqrt{2}} > 0 \quad ; \quad V(\phi_0) = -\frac{1}{4} h\, v^4$$

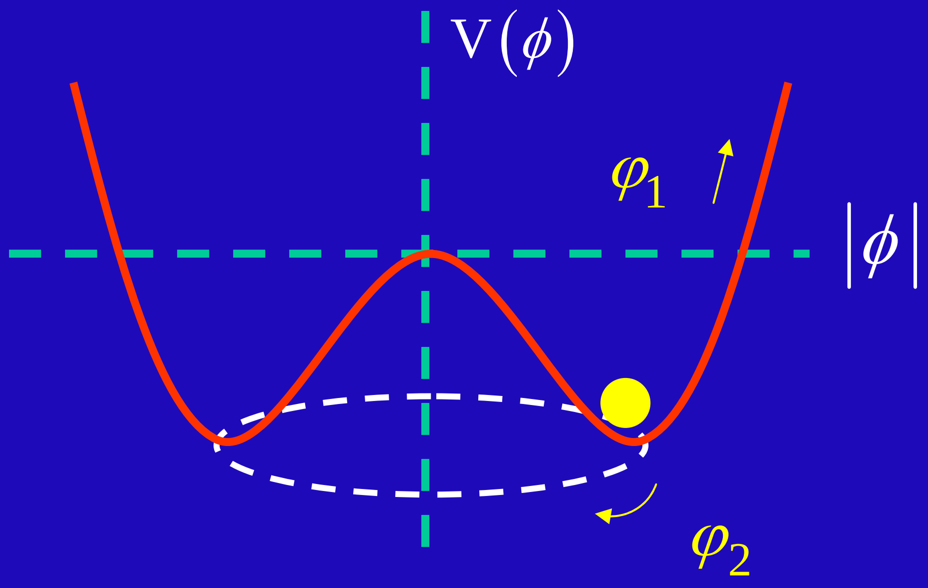
Spontaneous Symmetry Breaking:

$$\phi \equiv \frac{1}{\sqrt{2}} \left[v + \varphi_1(x) \right] e^{i\varphi_2(x)/v}$$

Vacuum Choice

Spontaneous Symmetry Breaking

$\mu^2 < 0$



$$\phi \equiv \frac{1}{\sqrt{2}}\left[\mathrm{v} + \varphi_1(x)\right] \, \mathrm{e}^{i\varphi_2(x)/\mathrm{v}}$$

$$\mathcal{L}(\phi) = \frac{1}{2}\partial_\mu\varphi_1\,\partial^\mu\varphi_1 + \frac{1}{2}\left(1+\frac{\varphi_1}{\mathrm{v}}\right)^2 \partial_\mu\varphi_2\,\partial^\mu\varphi_2 - V(\phi)$$

$$V(\phi) = V(\phi_0) + \frac{1}{2} M_{\varphi_1}^2\,\varphi_1^2 + h\,\mathrm{v}\,\varphi_1^3 + \frac{1}{4} h\,\varphi_1^4$$

$$M_{\varphi_1}^2 = -2\mu^2 > 0 \quad ; \quad M_{\varphi_2}^2 = 0$$

1 Massless Goldstone Boson

ELECTROWEAK SSB

New Scalar Doublet $\qquad \phi(x) \equiv \begin{pmatrix} \phi^{(+)}(x) \\ \phi^{(0)}(x) \end{pmatrix} \quad ; \quad y_\phi = Q_\phi - T_3 = \frac{1}{2}$

$$\mathcal{L}(\phi) = (\mathbf{D}_\mu \phi)^\dagger \, \mathbf{D}^\mu \phi - \mu^2 \; \phi^\dagger \phi - h \; (\phi^\dagger \phi)^2$$

$$\mathbf{D}^\mu \phi = \left[\partial^\mu - i\, g\, \mathbf{W}^\mu - i\, g'\, y_\phi\, B^\mu \right] \phi \qquad ; \qquad \mathbf{W}^\mu = \frac{\vec{\tau}}{2} \cdot \vec{W}^\mu$$

$SU(2)_L \otimes U(1)_Y$ **Symmetry**

Degenerate Vacuum States:

$(\mu^2 < 0 \;,\; h > 0)$

$$\left| \langle 0 | \, \phi^{(0)} \, | 0 \rangle \right| = \sqrt{\frac{-\mu^2}{2h}} \equiv \frac{v}{\sqrt{2}}$$

Spontaneous Symmetry Breaking:

$$\phi(x) = \exp\left\{ i \, \frac{\vec{\tau}}{2} \cdot \vec{\theta}(x) \right\} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

HIGGS MECHANISM

$$\phi(x) \;=\; \exp\left\{ i\,\frac{\vec{\tau}}{2}\cdot\vec{\theta}\,(x)\right\}\; \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \mathrm{v}+H\,(x)\end{pmatrix}$$

$\mathrm{SU(2)}_{\mathrm{L}}$ Invariance ➡ $\vec{\theta}(x)$ Unphysical

Unitary Gauge: $\vec{\theta}(x) \;=\; 0$

$$(\mathrm{D}_\mu\phi)^\dagger\,\mathrm{D}^\mu\phi \quad\longrightarrow\quad \frac{1}{2}\,\partial_\mu H\,\partial^\mu H \;+\; \frac{g^2}{4}\,(\mathrm{v}+H)^2\left\{ W_\mu^\dagger W^\mu + \frac{1}{2\cos^2\theta_W}\,Z_\mu Z^\mu \right\}$$

➡ $$\boxed{M_Z\;\cos\theta_W \;=\; M_W \;=\; \frac{1}{2}\,\mathrm{v}\,g}$$

Massive Gauge Bosons

Bosonic Degress of Freedom

Massless $W^{\pm}\,,\ Z$

3 X 2 helicities **= 6**

+

3 Goldstones $\vec{\theta}$

SSB ↓

Massive $W^{\pm}\,,\ Z$

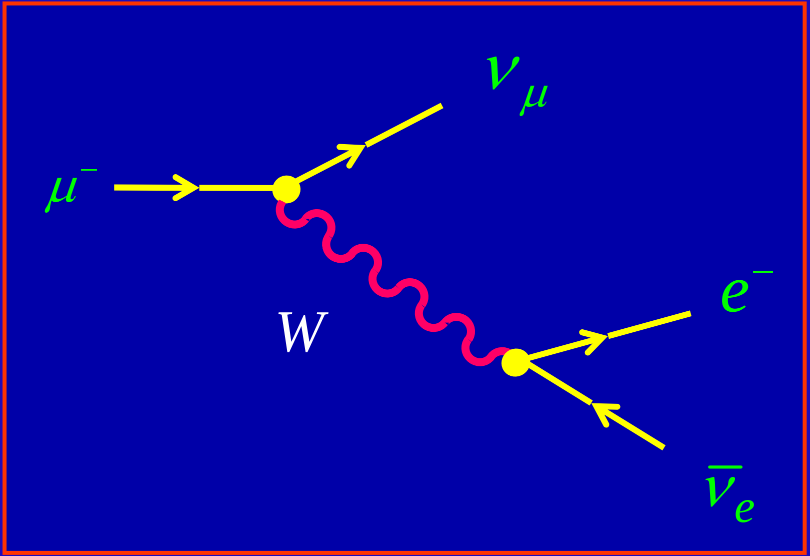
3 X 3 helicities **= 9**

SAME

PHYSICS

$$M_Z \cos\theta_W = M_W = \frac{1}{2}\, \mathrm{v}\, g$$

$$M_Z = 91.1875 \text{ GeV} > M_W = 80.425 \text{ GeV} \;\Rightarrow\; \sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2} = 0.222$$

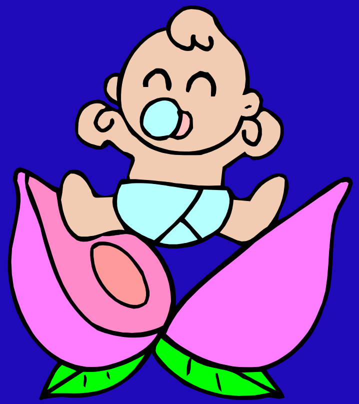


$$\frac{g^2}{M_W^2 - q^2} \approx \frac{g^2}{M_W^2} \equiv 4\sqrt{2}\, G_F$$

$$\frac{1}{\tau_\mu} \equiv \Gamma = \frac{G_F^2\, m_\mu^5}{192\,\pi^3}$$

$$\left.\begin{array}{l} G_F = 1.16637 \times 10^{-5} \text{ GeV}^{-2} \\ g = \dfrac{e}{\sin\theta_W} \quad , \quad M_W \end{array}\right\} \;\Rightarrow\; \begin{array}{l} \sin^2\theta_W = 0.215 \\ \mathrm{v} = \left(\sqrt{2}\, G_F\right)^{-1/2} = 246 \text{ GeV} \end{array}$$

THE HIGGS BOSON



$$\mathcal{L}_S = \frac{h\,\mathrm{v}^4}{4} + \mathcal{L}_H + \mathcal{L}_{HG^2}$$

$$\mathcal{L}_H = \frac{1}{2}\partial_\mu H\,\partial^\mu H - \frac{1}{2}M_H^2\,H^2 - \frac{M_H^2}{2\mathrm{v}}\,H^3 - \frac{M_H^2}{8\mathrm{v}^2}\,H^4$$

$$\mathcal{L}_{HG^2} = \left[M_W^2\,W_\mu^\dagger W^\mu + \frac{1}{2}M_Z^2\,Z_\mu Z^\mu\right]\left\{1 + \frac{2}{\mathrm{v}}H + \frac{H^2}{\mathrm{v}^2}\right\}$$

1 Scalar Particle H^0 to be Discovered

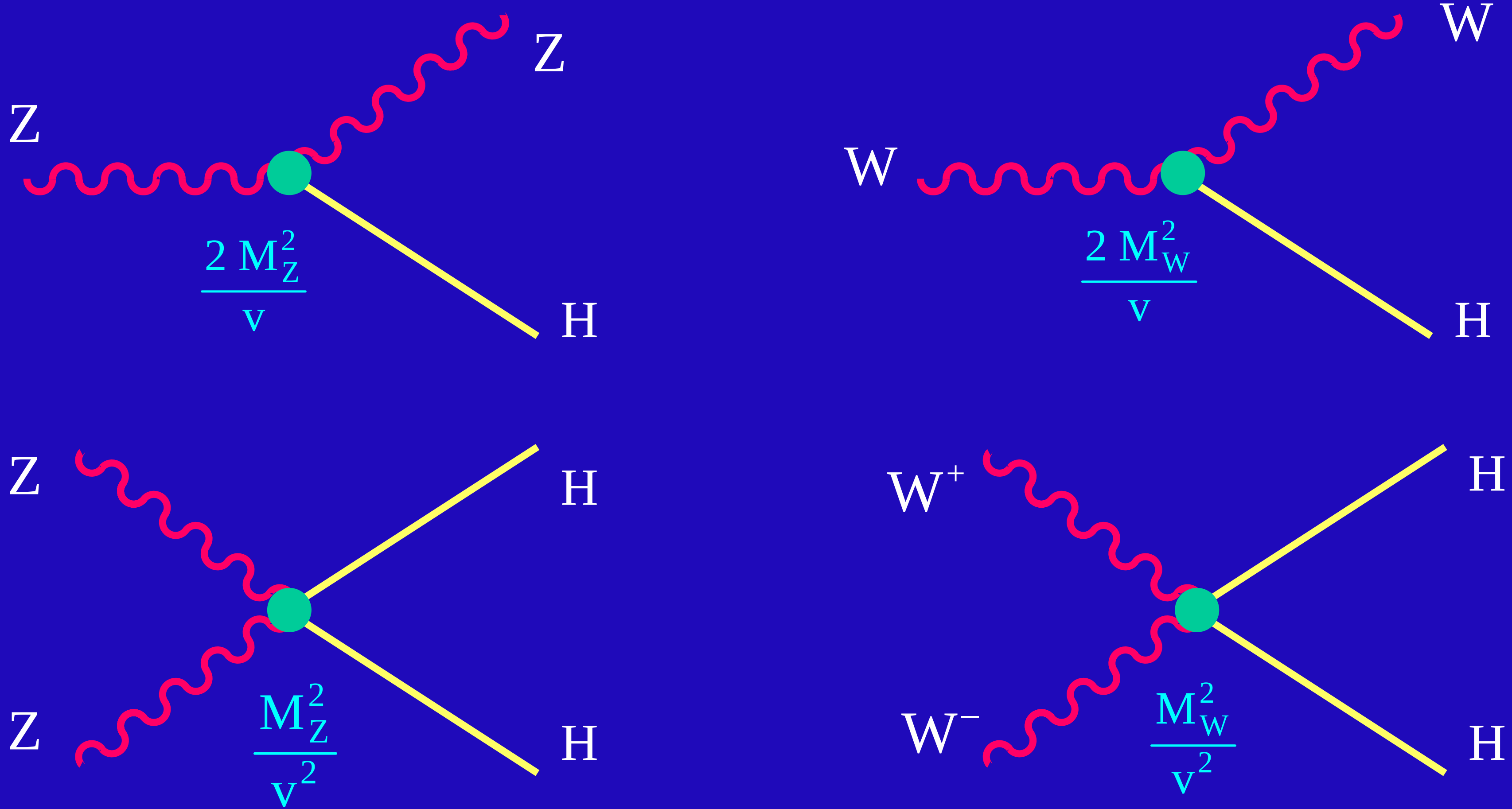
$$M_H = \sqrt{-2\mu^2} = \sqrt{2h}\,\mathrm{v}$$

Free Parameter

LEP: $114.4\ \mathrm{GeV} < M_H < 237\ \mathrm{GeV}$ (95% CL)

(Direct) (Indirect)

Higgs Couplings $\propto$ Masses



$$v = \left(\sqrt{2}\, G_F\right)^{-1/2} = 246 \quad \text{GeV}$$

FERMION MASSESS

Scalar – Fermion Couplings allowed by Gauge Symmetry

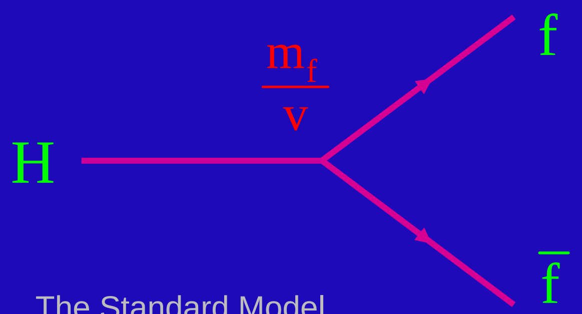
$$\mathcal{L}_Y = (\bar{q}_u, \bar{q}_d)_L \left[c^{(d)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} (q_d)_R + c^{(u)} \begin{pmatrix} \phi^{(0)\dagger} \\ -\phi^{(+)\dagger} \end{pmatrix} (q_u)_R \right] + (\bar{\nu}_l, \bar{l})_L \; c^{(l)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} l_R + \text{h.c.}$$

$\Downarrow$ **SSB**

$$\mathcal{L}_Y = -\left(1 + \frac{H}{v}\right) \left\{ m_{q_d} \, \bar{q}_d \, q_d + m_{q_u} \, \bar{q}_u \, q_u + m_l \, \bar{l} \, l \right\}$$

Fermion Masses are New Free Parameters

$$\left[m_{q_d} , m_{q_u} , m_l \right] = - \left[c^{(d)} , c^{(u)} , c^{(l)} \right] \frac{v}{\sqrt{2}}$$



Couplings Fixed: $$g_{Hf\bar{f}} = \frac{m_f}{v}$$

Quarks Leptons Bosons