The Fundamental Interactions after the Higgs Discovery

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arXiv:1201.0537 (Standard Model)

arXiv:1512.08749 (Higgs Physics)

arXiv:1805.08597 (Flavour Physics)

Escuela Avanzada de Verano, México, 19-23 July 2021

PROBLEM WITH MASSES

The same symmetry that determines the interactions requires all elementary particles to be massless

$$\mathcal{L}_{m_f} \equiv -m_f\ \bar{f}\ f\ = -m_f\ (\bar{f}_L\ f_R + \bar{f}_R\ f_L)$$

Not gauge invariant ➡ $m_f = 0$

$$m_\gamma = m_G = 0$$

$$M_W = 80.38\ \text{GeV}$$

$$M_Z = 91.19\ \text{GeV}$$

$$m_t = 173\ \text{GeV}$$

?

Mass is the only difference among the 3 families of quarks and leptons

PROBLEM WITH MASSES

- If $M_W = M_Z = 0$ the weak force would not be suppressed

  Stars (Sun) would consume much faster their nuclear fuel

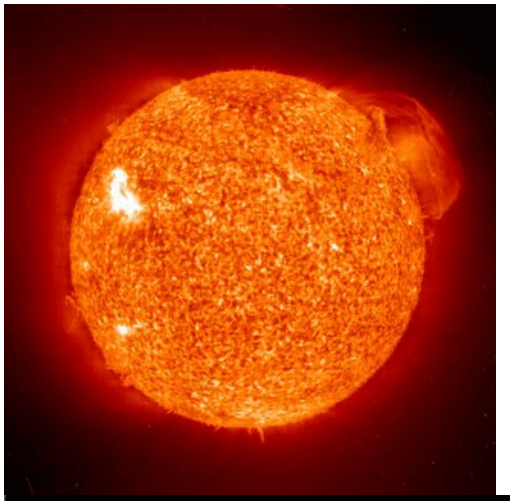
  The Universe would be different

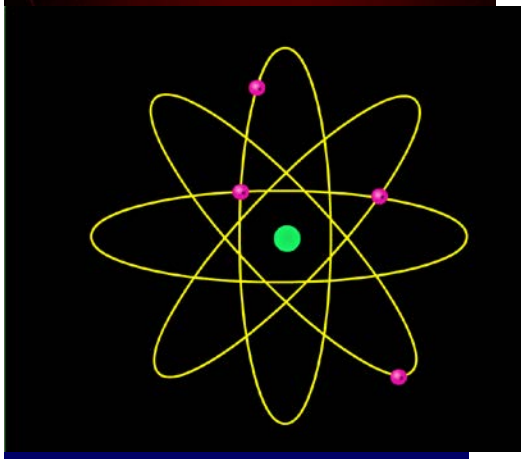
- Massless electrons would travel at the speed of light

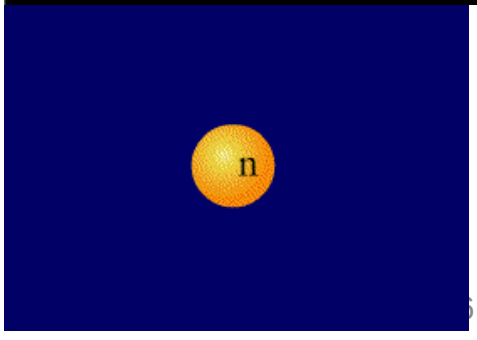
  Atoms would not exist

- If $m_u > m_d$ protons would decay

  Many atomic nuclei would not be stable



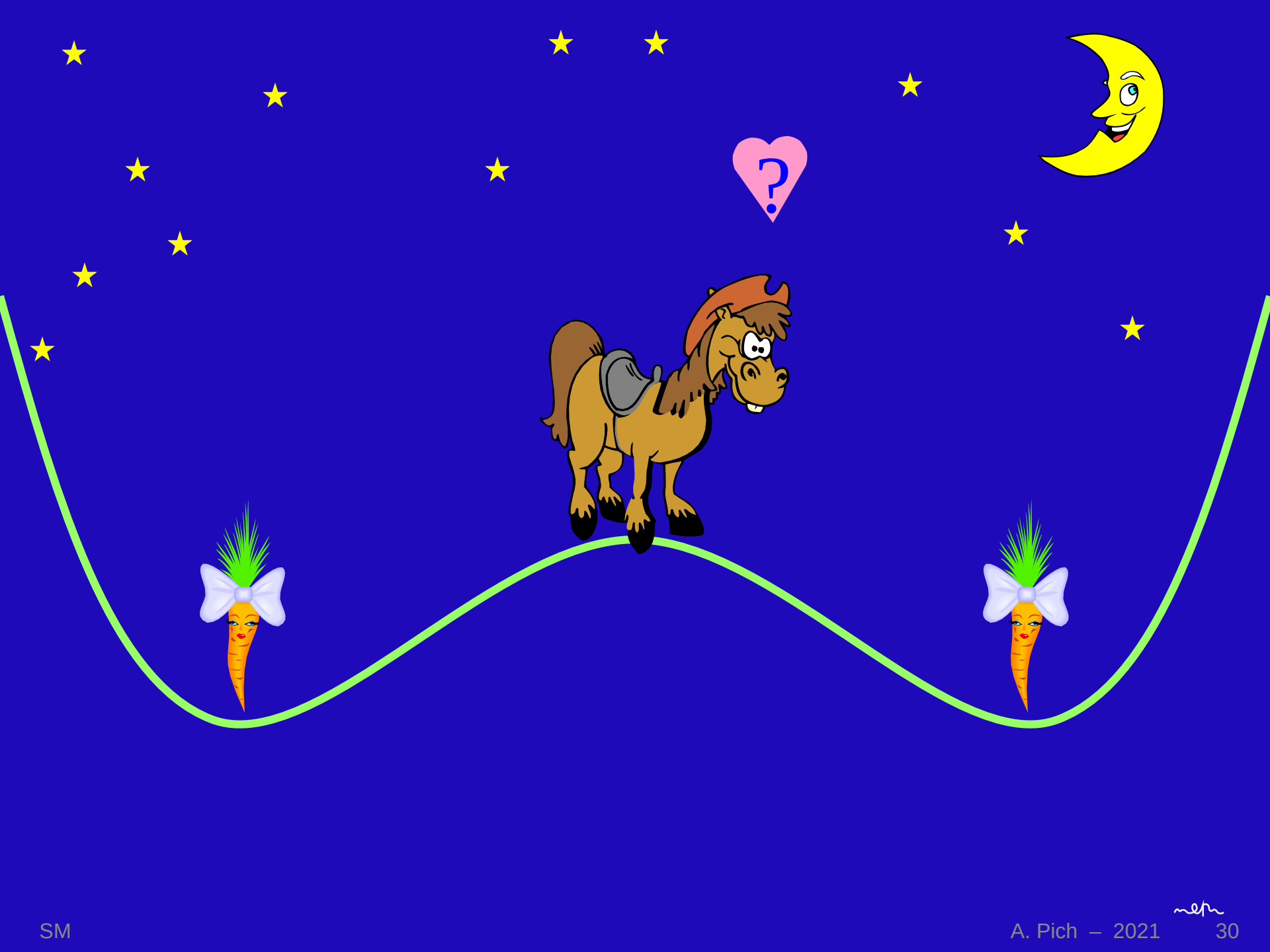


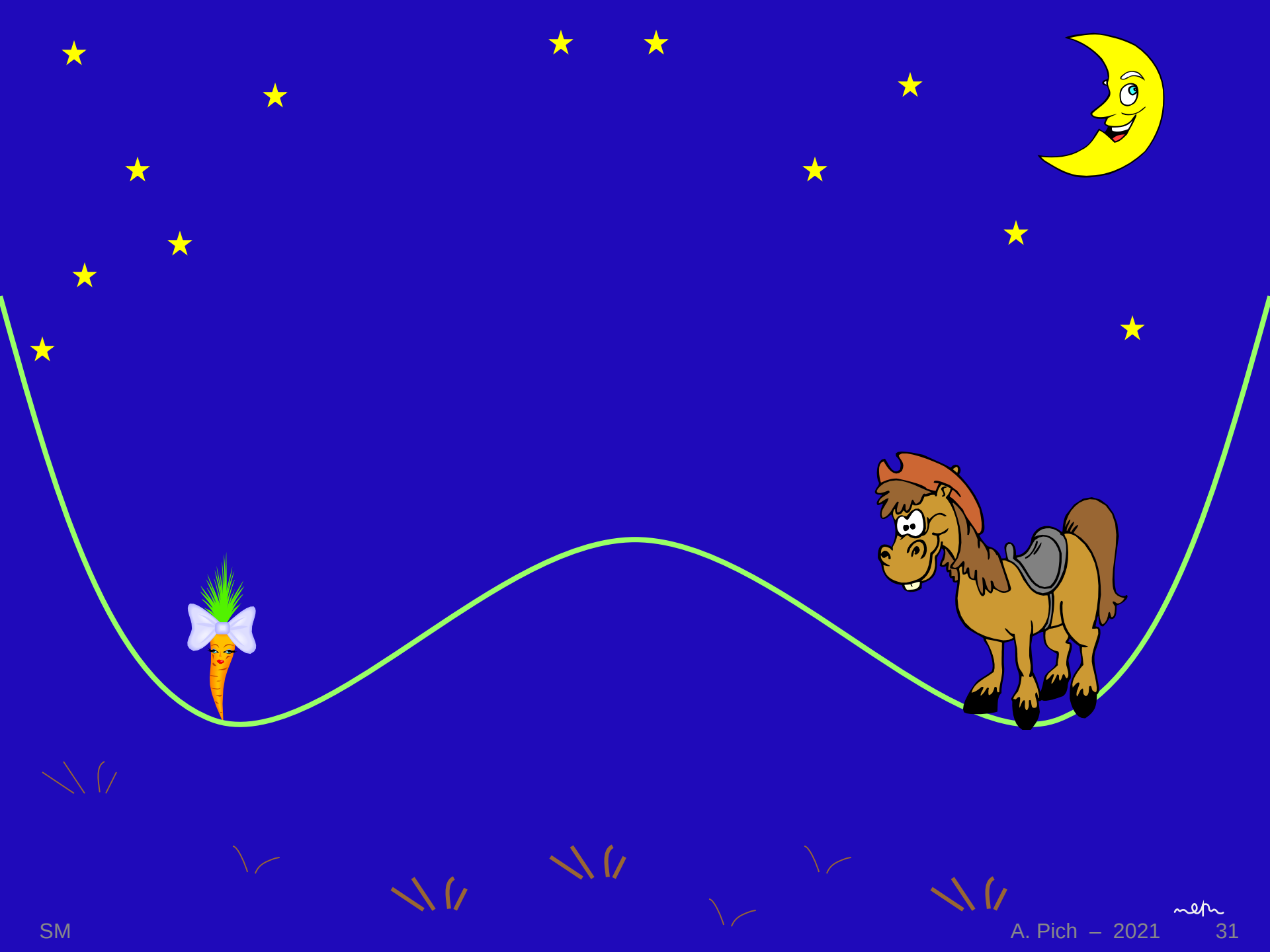


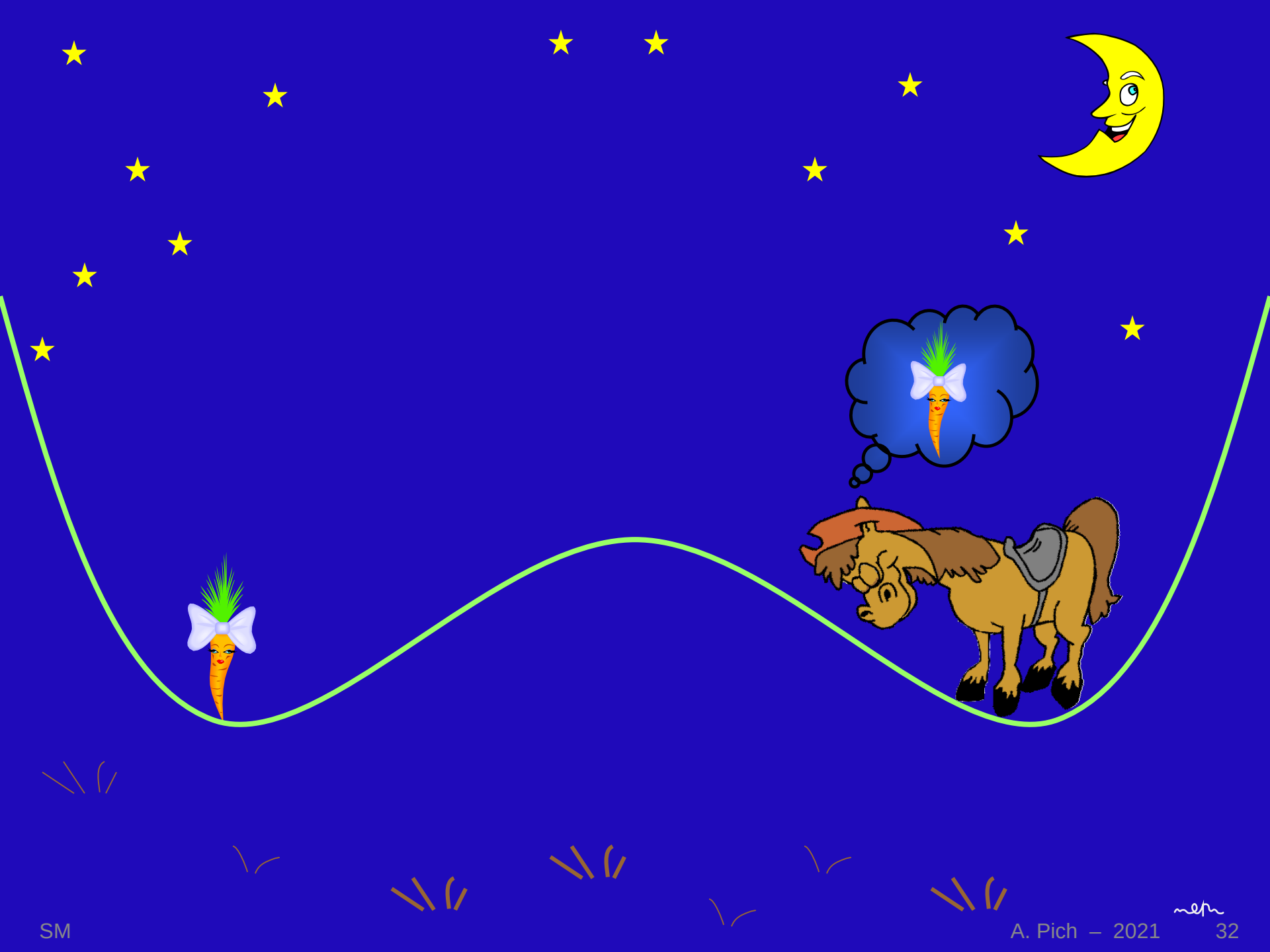
Masses cannot be added by hand: the quantum theory becomes ill-defined when gauge symmetry is broken

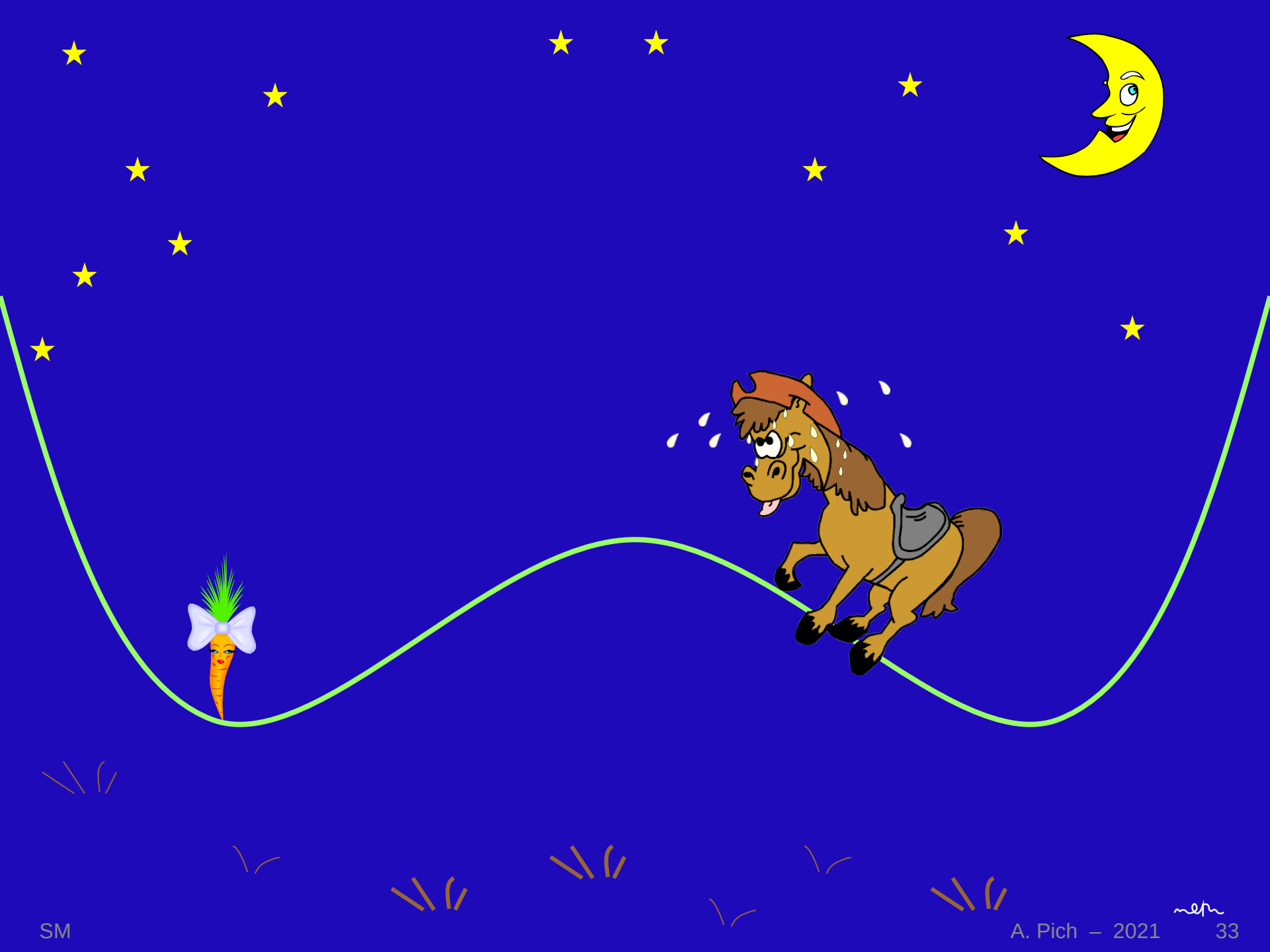
Spontaneous Symmetry Breaking

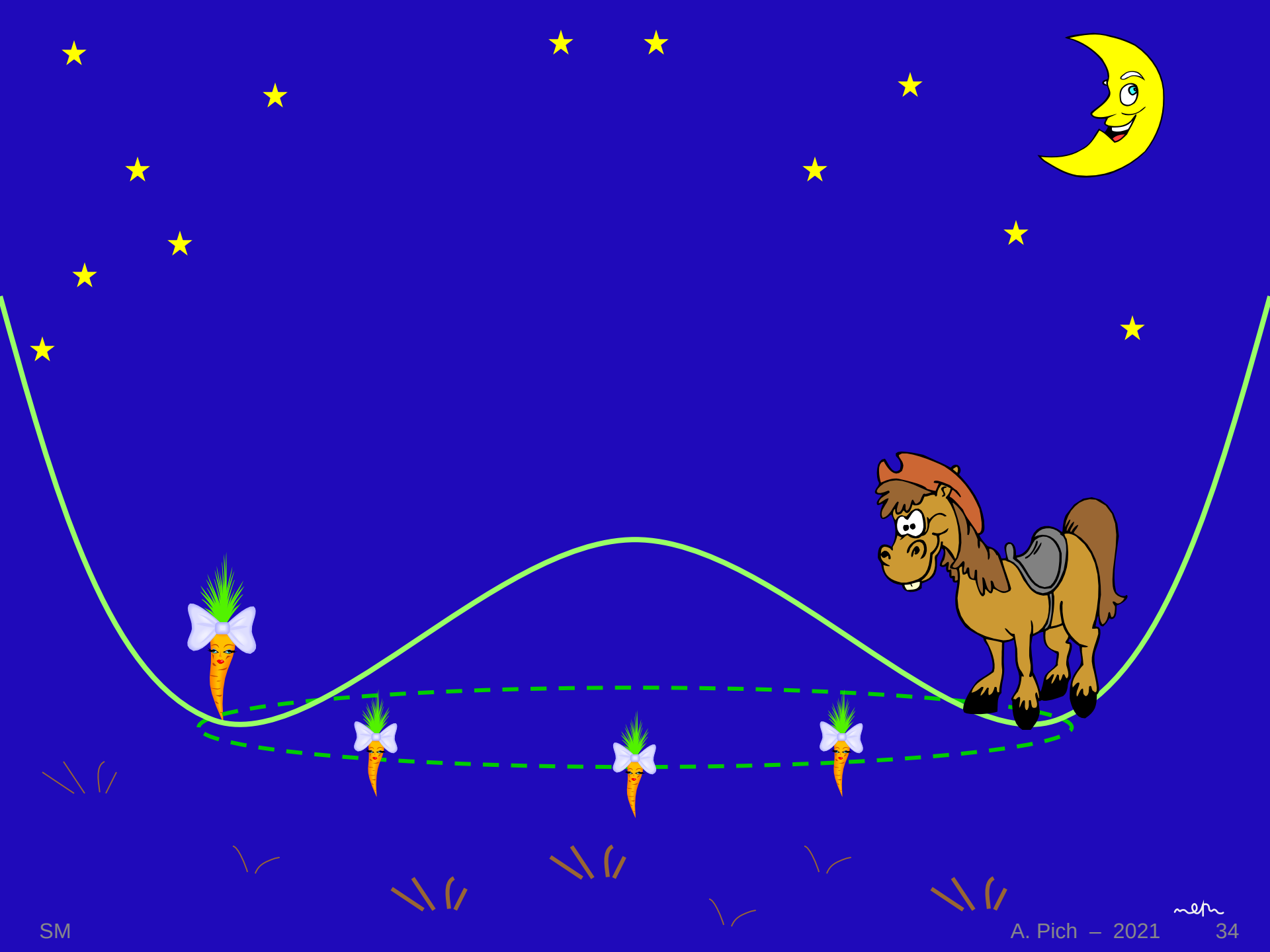
Spontaneous Symmetry Breaking











Nobel Prize 2008

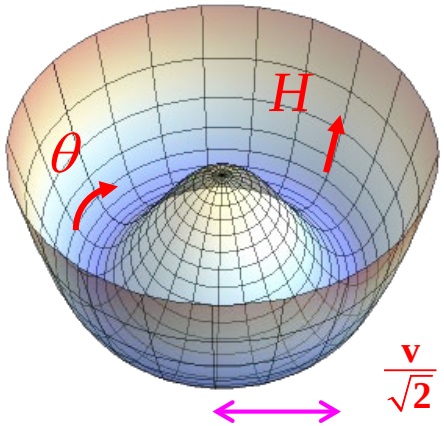
Y. Nambu

J. Goldstone

Higgs Mechanism

$$V(\phi) = -\mu^2 \phi^\dagger\phi + \lambda \left(\phi^\dagger\phi\right)^2 \quad , \quad v \equiv \sqrt{\mu^2/\lambda}$$

Nobel Prize 2013



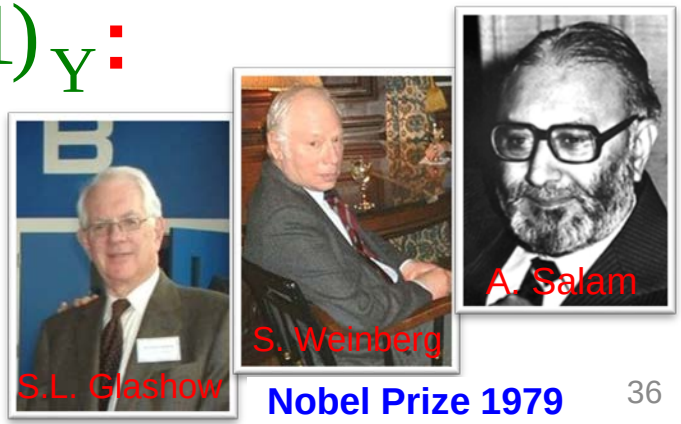
- **Scalar field (without spin) coupled to the gauge field**
- **θ(x) + Gauge Field = Massive Gauge Field**
- **H(x) = Higgs Field**

$$\phi(x) = \frac{1}{\sqrt{2}}\, e^{i\theta(x)} \left[v + H(x)\right]$$

Standard Theory $SU(2)_L \otimes U(1)_Y$:

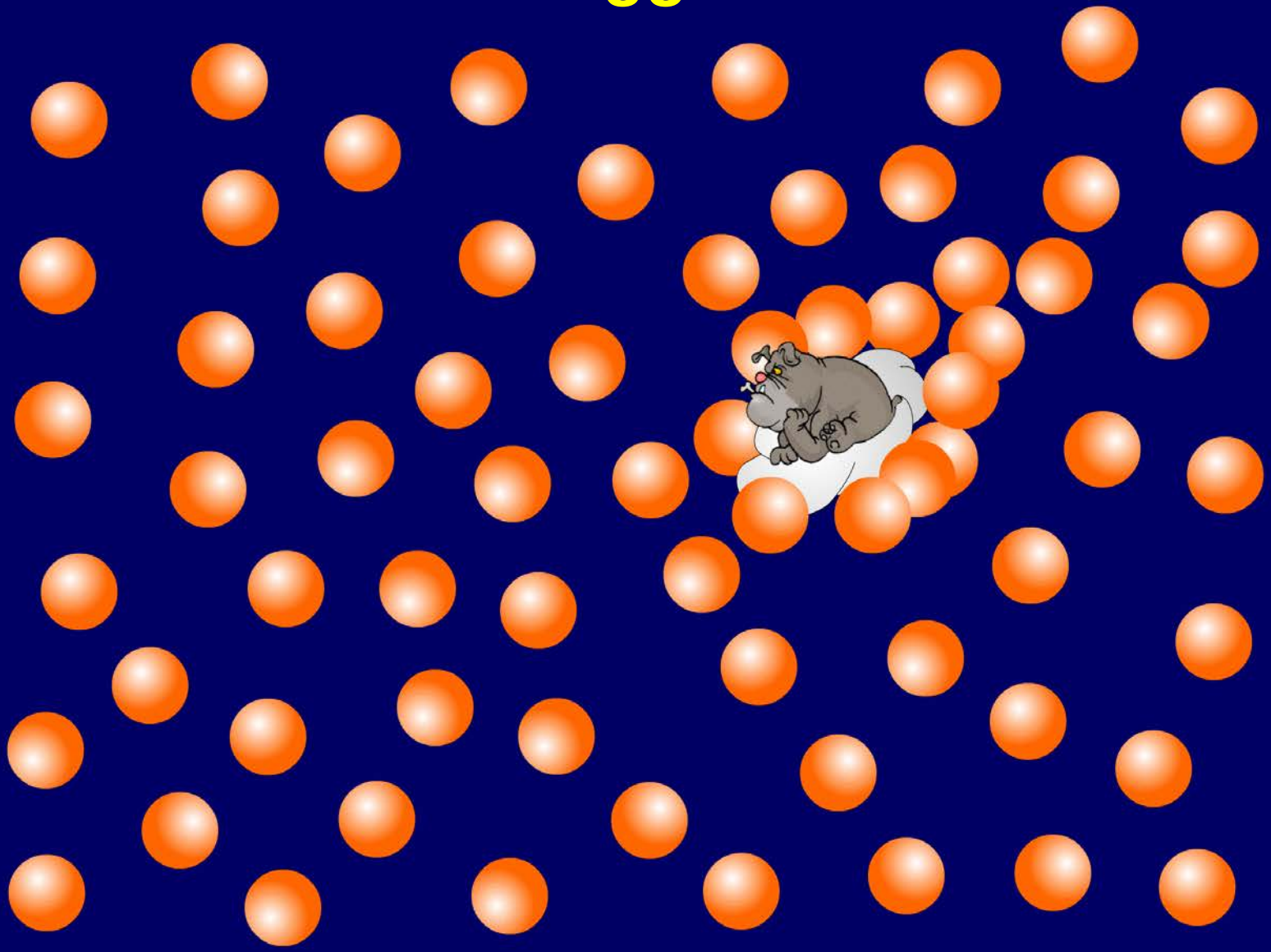
$$M_Z \cos\theta_W = M_W = \frac{1}{2} v\, g$$

v = 246 GeV



Nobel Prize 1979

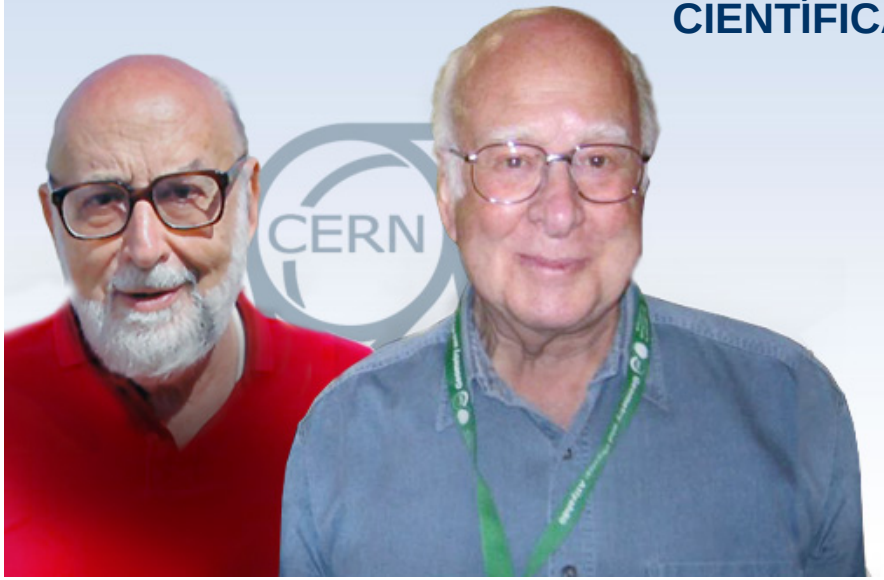
Masses generated through the interaction with the Higgs field



The discovery of the Higgs Boson

PREMIO PRÍNCIPE DE ASTURIAS DE INVESTIGACIÓN CIENTÍFICA Y TÉCNICA 2013

Fundación Príncipe de Asturias

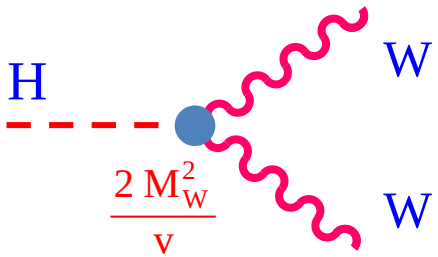


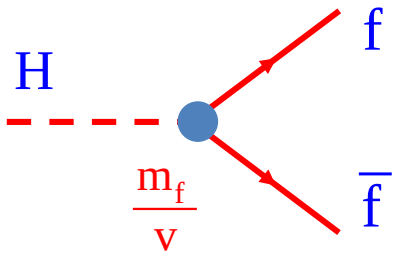
The Nobel Prize in Physics 2013: François Englert, Peter Higgs

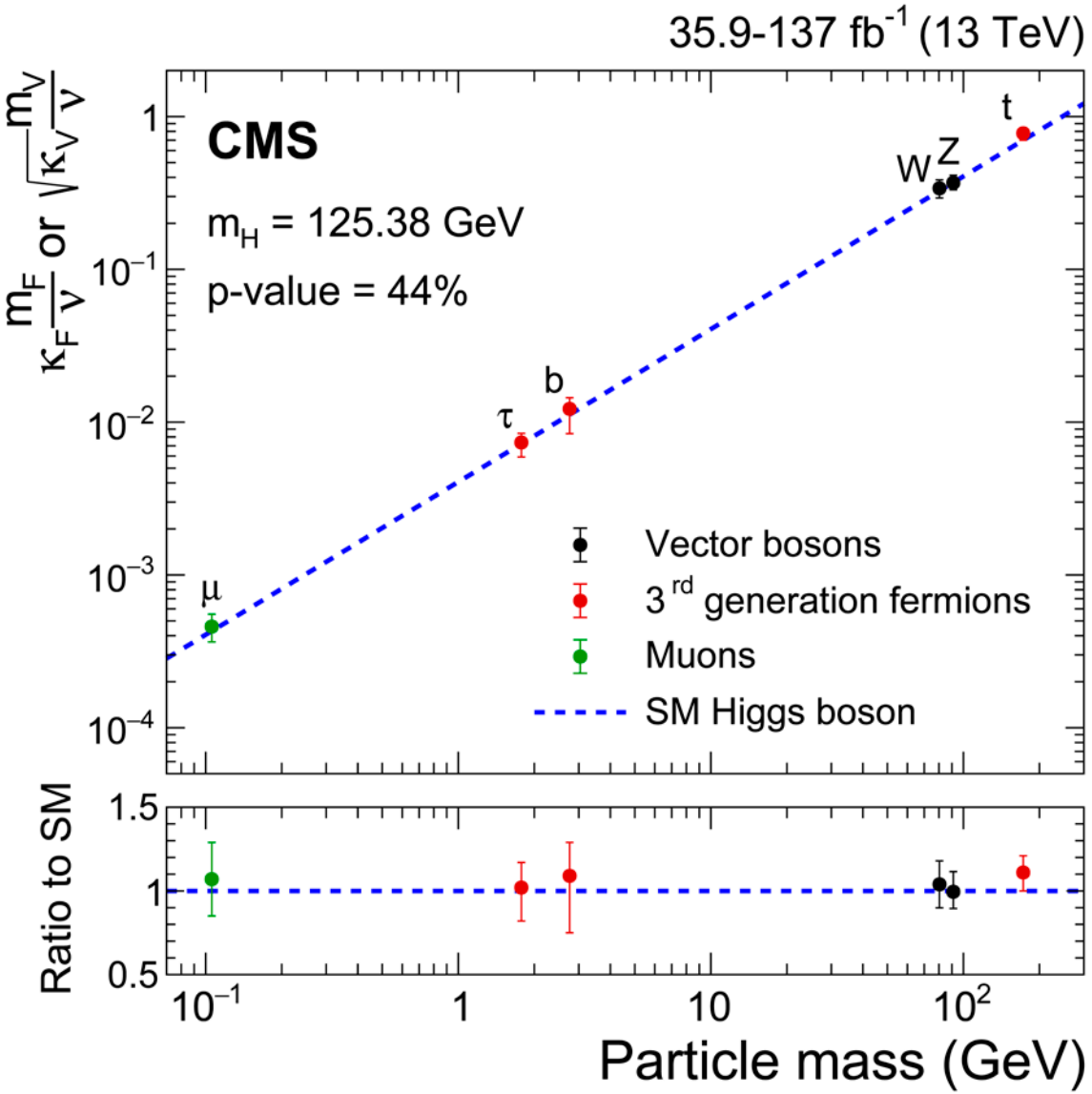
"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

A Higgs field indeed

Interaction proportional to mass







Flavour Structure of the Standard Model

$$\begin{pmatrix} u & \nu_e \\ d & e^- \end{pmatrix} , \begin{pmatrix} c & \nu_\mu \\ s & \mu^- \end{pmatrix} , \begin{pmatrix} t & \nu_\tau \\ b & \tau^- \end{pmatrix}$$

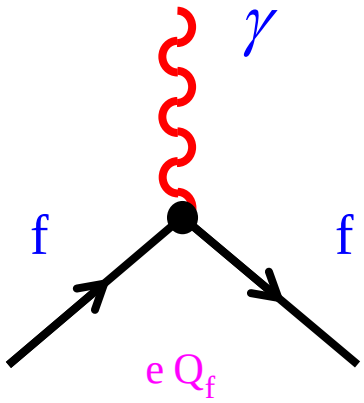
- **Pattern of masses**
- **Flavour Mixing**
- $\not{CP}$

Related to SSB

Scalar Sector (Higgs)

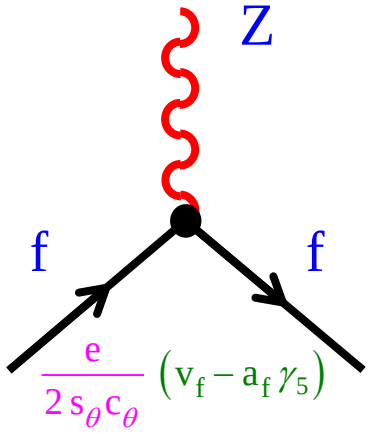
- **Kaon Factories :** u , d , s
- **τcF :** c , τ
- **BF:** b , c , τ
- **LHC :** t , b , c
- **LC, FCC :** t , b , c, τ
- **νF :** ν_e , ν_μ , ν_τ

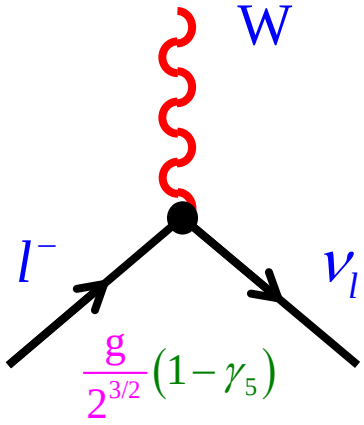
Universality: Family–Independent Couplings



NEUTRAL CURRENTS

Flavour Conserving

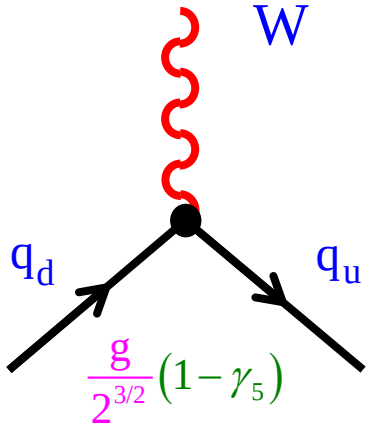


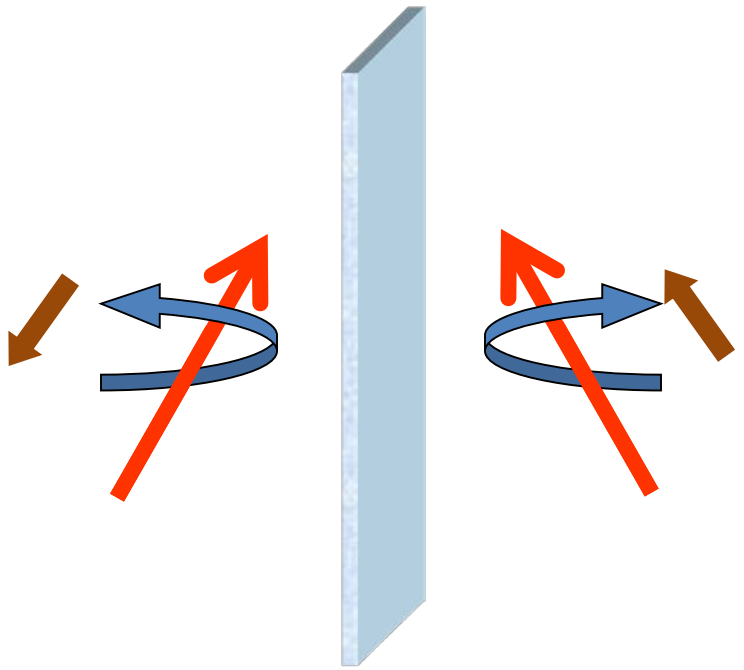


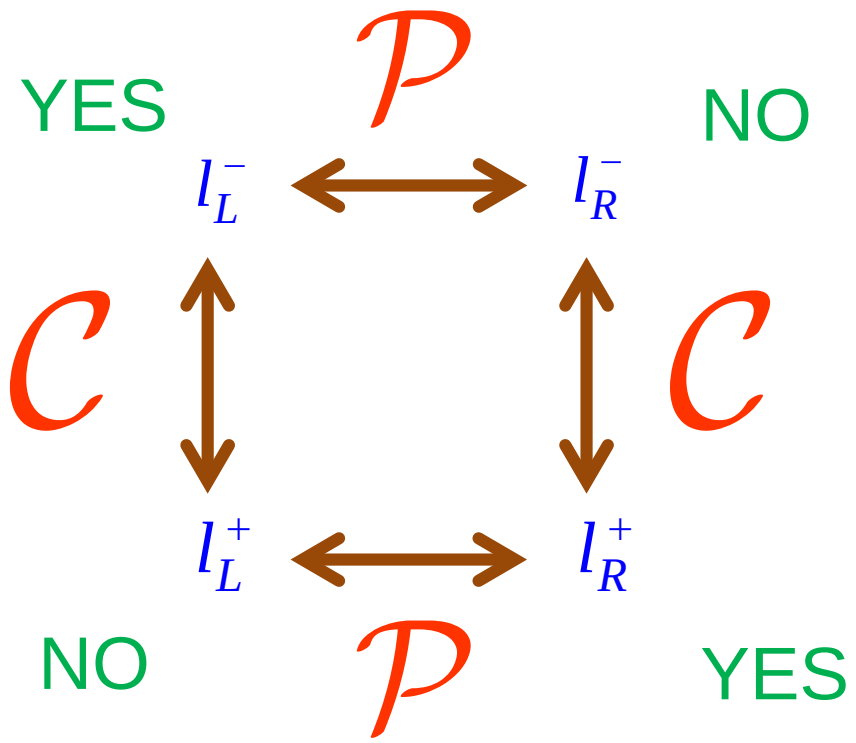
CHARGED CURRENTS

Flavour Changing

Left Handed







$\not{\mathcal{P}}$ **and** $\not{\mathcal{C}}$ **in Weak Interactions**

$\mathcal{CP}$ **still a good symmetry** **(1 family)**

FERMION MASSES

Scalar – Fermion Couplings allowed by Gauge Symmetry

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

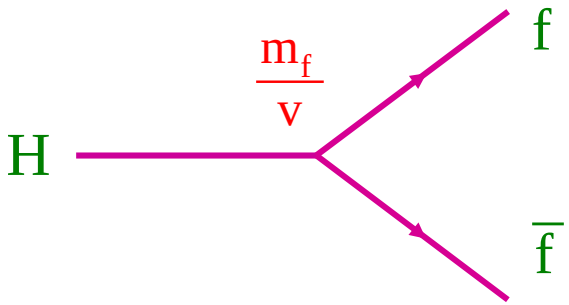
$$\phi^{(0)} \to \frac{1}{\sqrt{2}} (v + H) \quad , \quad \phi^{(+)} \to 0$$

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: $g_{H f \bar{f}} = \dfrac{m_f}{v}$

FERMION GENERATIONS

$N_G = 3$ Identical Copies — **Masses are the only difference**

$$\begin{matrix} Q=0 \\ Q=-1 \end{matrix} \quad \begin{pmatrix} \nu'_j & u'_j \\ l'_j & d'_j \end{pmatrix} \quad \begin{matrix} Q=+2/3 \\ Q=-1/3 \end{matrix} \qquad (j=1,\cdots,N_G)$$

WHY ?

$$\mathcal{L}_Y = -\sum_{jk} \left\{ \left(\overline{u}'_j, \overline{d}'_j\right)_L \left[c^{(d)}_{jk} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} d'_{kR} + c^{(u)}_{jk} \begin{pmatrix} \phi^{(0)\dagger} \\ -\phi^{(+)\dagger} \end{pmatrix} u'_{kR} \right] - \left(\overline{\nu}'_j, \overline{l}'_j\right)_L c^{(l)}_{jk} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} l'_{kR} \right\} + \text{h.c.}$$

SSB

$$\mathcal{L}_Y = -\left(1+\frac{H}{v}\right) \left\{ \overline{d}'_L \cdot \mathbf{M}'_d \cdot d'_R + \overline{u}'_L \cdot \mathbf{M}'_u \cdot u'_R + \overline{l}'_L \cdot \mathbf{M}'_l \cdot l'_R + \text{h.c.} \right\}$$

Arbitrary Non-Diagonal Complex Mass Matrices

$$\left[\mathbf{M}'_d \, , \mathbf{M}'_u \, , \mathbf{M}'_l \right]_{jk} = \left[c^{(d)}_{jk} \, , c^{(u)}_{jk} \, , c^{(l)}_{jk} \right] \frac{v}{\sqrt{2}}$$

DIAGONALIZATION OF MASS MATRICES

$$\mathbf{M}'_d = \mathbf{H}_d \cdot \mathbf{U}_d = \mathbf{S}_d^\dagger \cdot \mathcal{M}_d \cdot \mathbf{S}_d \cdot \mathbf{U}_d$$
$$\mathbf{M}'_u = \mathbf{H}_u \cdot \mathbf{U}_u = \mathbf{S}_u^\dagger \cdot \mathcal{M}_u \cdot \mathrm{S}_u \cdot \mathbf{U}_u$$
$$\mathbf{M}'_l = \mathbf{H}_l \cdot \mathbf{U}_l = \mathbf{S}_l^\dagger \cdot \mathcal{M}_l \cdot \mathbf{S}_l \cdot \mathbf{U}_l$$

$$\mathbf{H}_\mathrm{f} = \mathbf{H}_\mathrm{f}^\dagger$$
$$\mathbf{U}_\mathrm{f} \cdot \mathbf{U}_\mathrm{f}^\dagger = \mathbf{U}_\mathrm{f}^\dagger \cdot \mathbf{U}_\mathrm{f} = 1$$
$$\mathbf{S}_\mathrm{f} \cdot \mathbf{S}_\mathrm{f}^\dagger = \mathbf{S}_\mathrm{f}^\dagger \cdot \mathbf{S}_\mathrm{f} = 1$$

$$\mathcal{L}_Y = -\left(1+\frac{H}{\mathrm{v}}\right)\left\{\bar{\mathrm{d}}\cdot\mathcal{M}_d\cdot\mathrm{d} + \bar{\mathrm{u}}\cdot\mathcal{M}_u\cdot\mathrm{u} + \bar{l}\cdot\mathcal{M}_l\cdot l\right\}$$

$$\mathcal{M}_u = \mathrm{diag}\,(m_u, m_c, m_t) \quad ; \quad \mathcal{M}_d = \mathrm{diag}\,(m_d, m_s, m_b) \quad ; \quad \mathcal{M}_l = \mathrm{diag}\,(m_e, m_\mu, m_\tau)$$

$$\mathrm{d}_L \equiv \mathbf{S}_d \cdot \mathrm{d}'_L \quad ; \quad \mathrm{u}_L \equiv \mathbf{S}_u \cdot \mathrm{u}'_L \quad ; \quad l_L \equiv \mathbf{S}_l \cdot l'_L$$
$$\mathrm{d}_R \equiv \mathbf{S}_d \cdot \mathbf{U}_d \cdot \mathrm{d}'_R \quad ; \quad \mathrm{u}_R \equiv \mathbf{S}_u \cdot \mathbf{U}_u \cdot \mathrm{u}'_R \quad ; \quad l_R \equiv \mathbf{S}_l \cdot \mathbf{U}_l \cdot l'_R$$

Mass Eigenstates
$\neq$
Weak Eigenstates

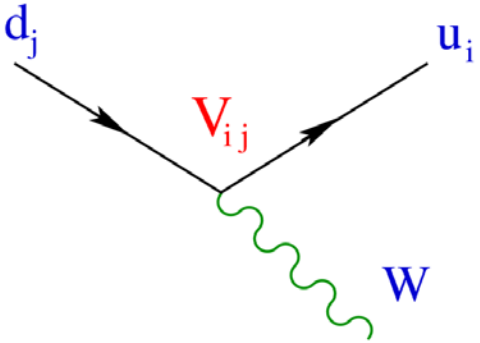
$$\bar{\mathrm{f}}'_L\,\mathrm{f}'_L = \bar{\mathrm{f}}_L\,\mathrm{f}_L \quad ; \quad \bar{\mathrm{f}}'_R\,\mathrm{f}'_R = \bar{\mathrm{f}}_R\,\mathrm{f}_R \quad \Rightarrow \quad \mathcal{L}'_{\mathrm{NC}} = \mathcal{L}_{\mathrm{NC}}$$

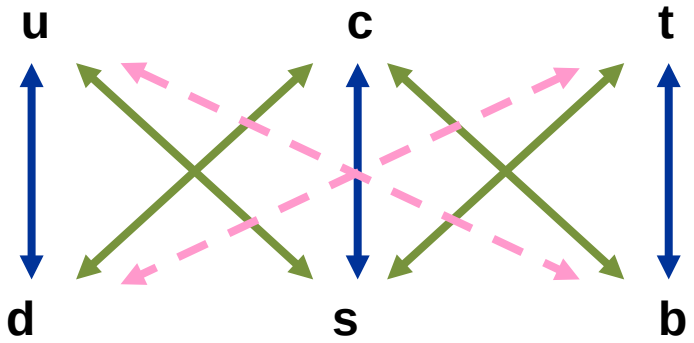
$$\bar{\mathrm{u}}'_L\,\mathrm{d}'_L = \bar{\mathrm{u}}_L \cdot \mathbf{V} \cdot \mathrm{d}_L \quad ; \quad \mathbf{V} \equiv \mathbf{S}_u \cdot \mathbf{S}_d^\dagger \quad \Rightarrow \quad \mathcal{L}'_{\mathrm{CC}} \neq \mathcal{L}_{\mathrm{CC}}$$

QUARK MIXING

Flavour Changing Charged Currents

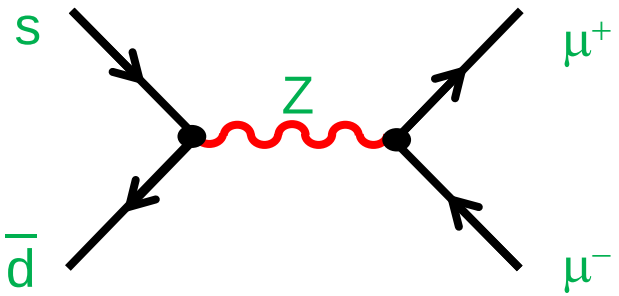
$$\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}} W_\mu^\dagger \left[\sum_{ij} \bar{u}_i \gamma^\mu (1-\gamma_5) V_{ij} d_j + \sum_l \bar{\nu}_l \gamma^\mu (1-\gamma_5) l \right] + \text{h.c.}$$





Flavour Conserving Neutral Currents (GIM)

NO

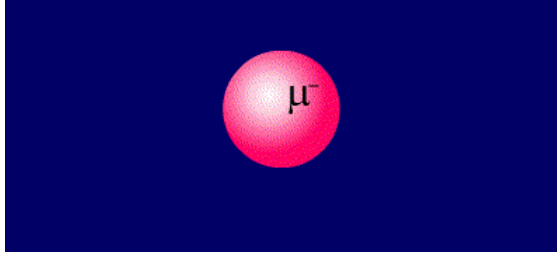


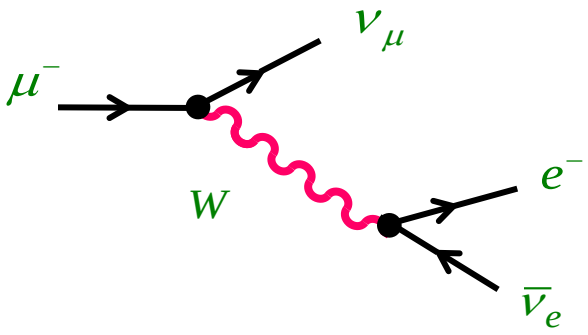
LHCb, 2001.10354

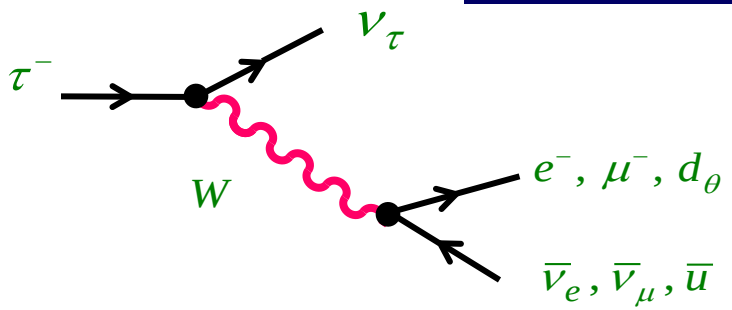
$$\text{Br}(K_S \to \mu^+\mu^-) < 2.1\times10^{-10}$$

(90% CL)

Weak Decays





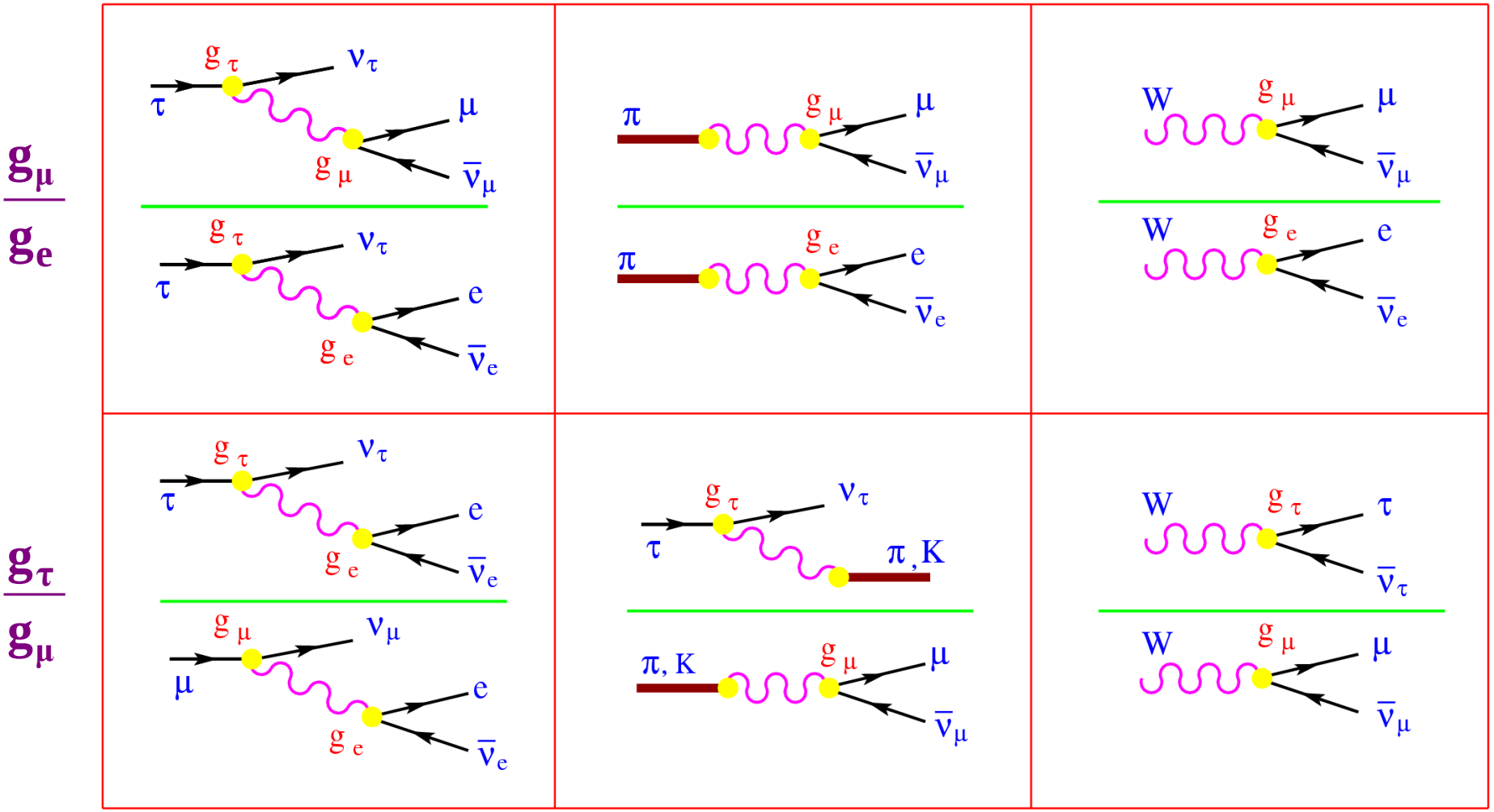


$$T(l \to \nu_l\, l'\bar{\nu}_{l'}) \sim \frac{g^2}{M_W^2 - q^2} \xrightarrow{q^2 << M_W^2} \frac{g^2}{M_W^2} = 4\sqrt{2}\, G_F$$

$$\frac{1}{\tau_\mu} = \frac{G_F^2\, m_\mu^5}{192\,\pi^3}\, f(m_e^2/m_\mu^2)\, r_{EW} \Rightarrow G_F = (1.166\,378\,7 \pm 0.000\,000\,6) \times 10^{-5}\ \text{GeV}^{-2}$$

$$r_{EW} = \left[1 + \frac{\alpha(m_\mu)}{2\pi}\left(\frac{25}{4} - \pi^2\right) + C_2 \frac{\alpha(m_\mu)^2}{\pi^2}\right] = 0.9958 \quad ; \quad f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \log x$$

LEPTON UNIVERSALITY



CHARGED CURRENT UNIVERSALITY

A. Pich, arXiv:2012.07099

$|g_\mu / g_e|$

$B_{\tau\to\mu}/B_{\tau\to e}$	1.0017 ± 0.0016
$B_{\pi\to\mu}/B_{\pi\to e}$	1.0010 ± 0.0009
$B_{K\to\mu}/B_{K\to e}$	0.9978 ± 0.0018
$B_{K\to\pi\mu}/B_{K\to\pi e}$	1.0010 ± 0.0025
$B_{W\to\mu}/B_{W\to e}$	0.998 ± 0.004

$|g_\tau / g_\mu|$

$B_{\tau\to e}\ \tau_\mu/\tau_\tau$	1.0011 ± 0.0014
$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	0.9965 ± 0.0026
$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	0.986 ± 0.007
$B_{W\to\tau}/B_{W\to\mu}$	1.004 ± 0.016

$|g_\tau / g_e|$

$B_{\tau\to\mu}\ \tau_\mu/\tau_\tau$	1.0028 ± 0.0015
$B_{W\to\tau}/B_{W\to e}$	1.022 ± 0.012

0.997 ± 0.011 (CMS preliminary)