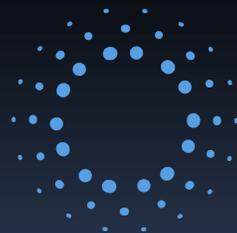


6ª Escola de Física  
PUC-Rio

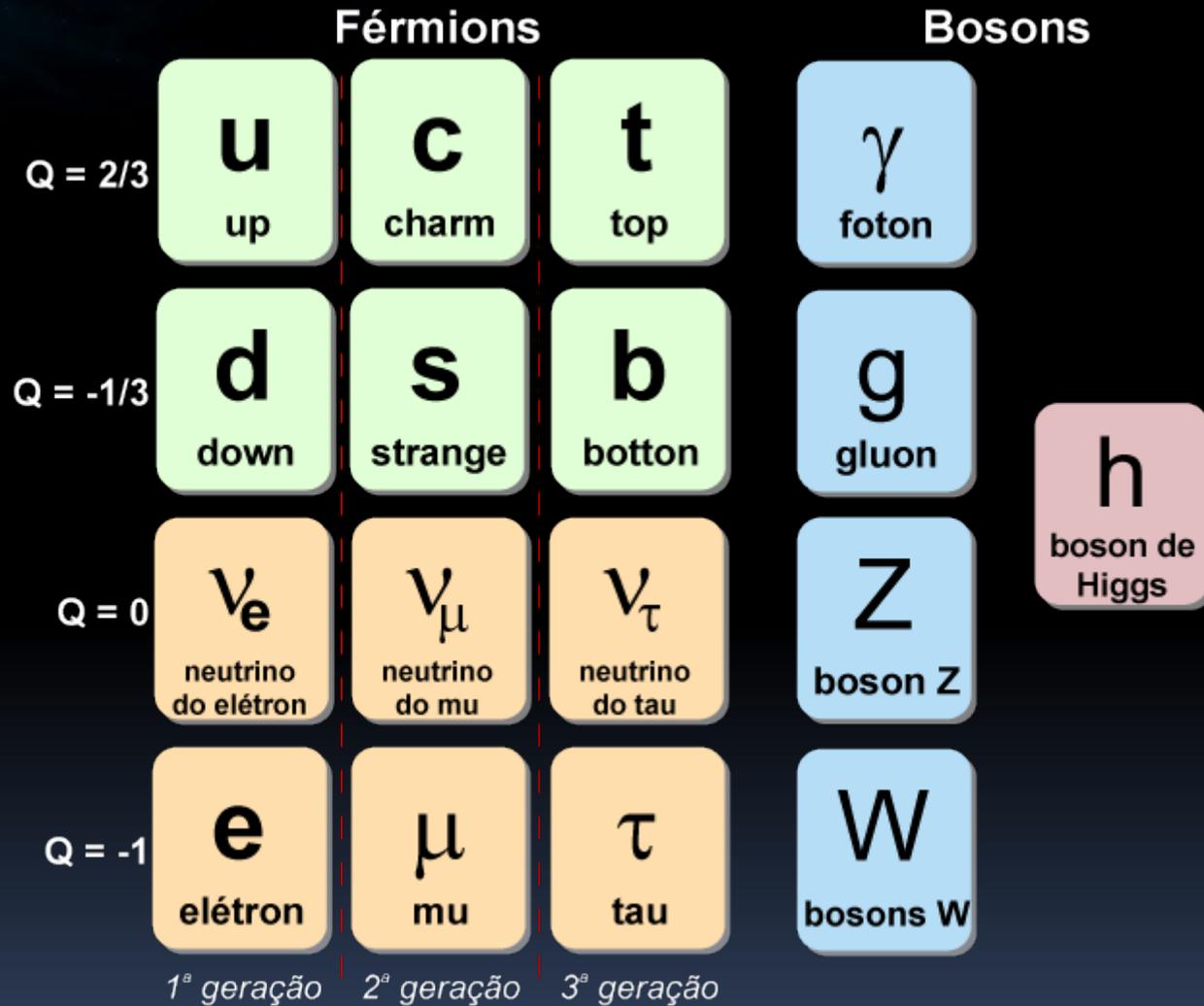
# Ideias Fundamentais da Física de Partículas

Ricardo D'Elia Matheus

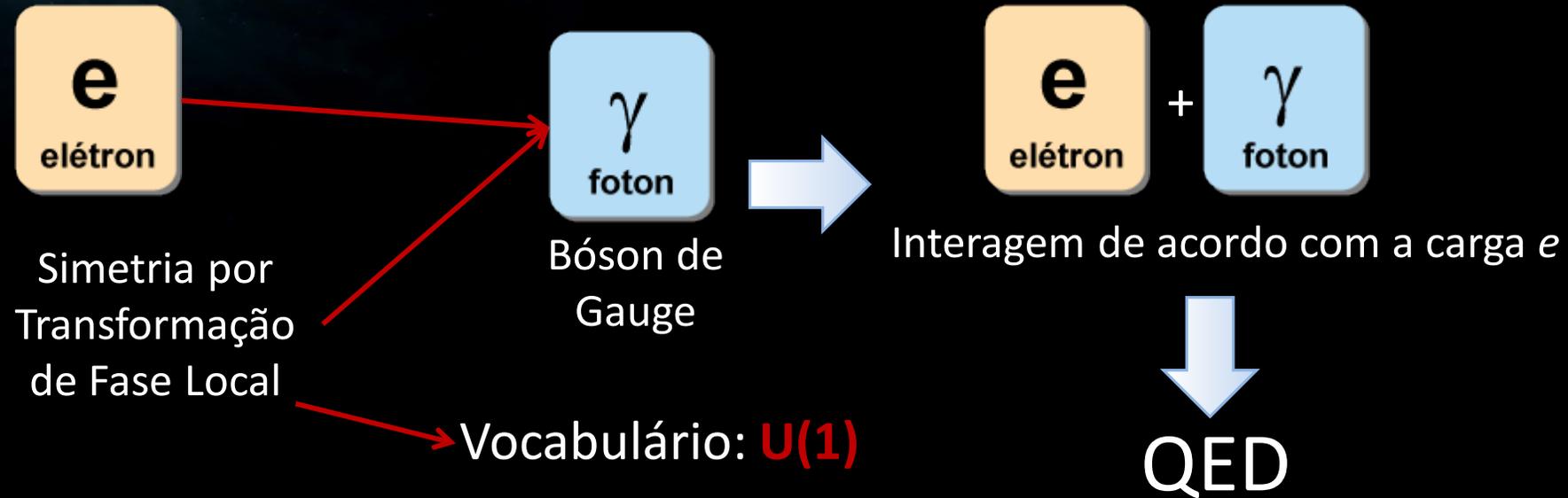


IFT - UNESP  
INSTITUTO DE FÍSICA TEÓRICA

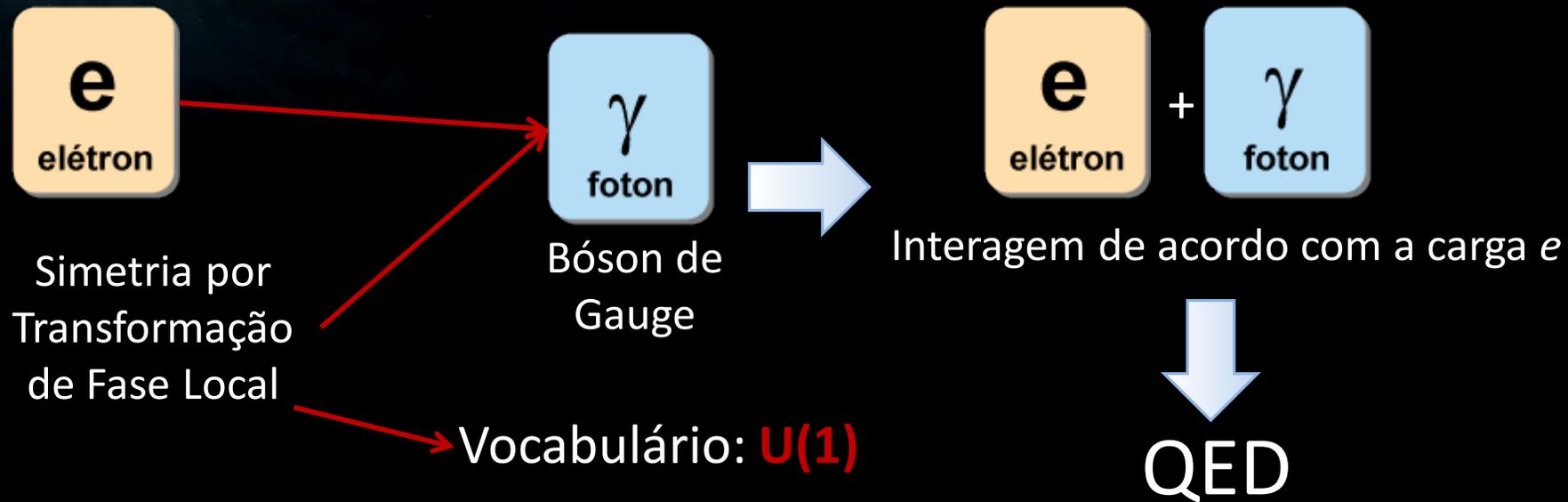
# O modelo padrão!



# Eletrodinâmica Quântica (QED)



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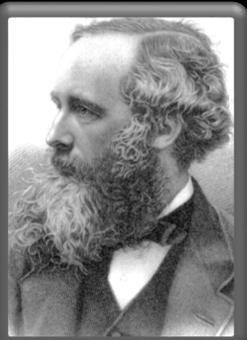
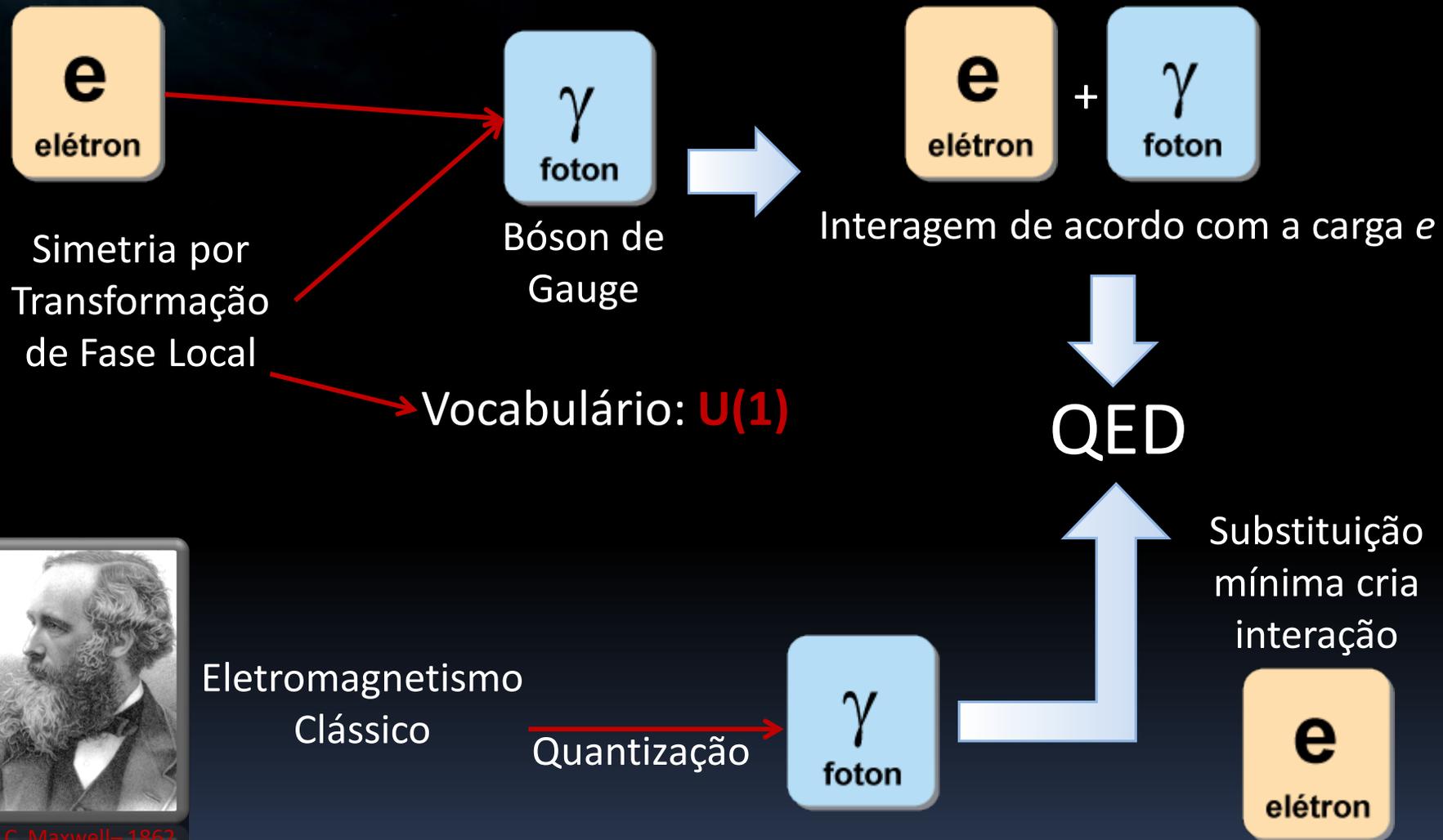
$$\left. \begin{aligned}
 \psi &\xrightarrow{U(1)} e^{i\theta(x)} \psi \\
 A_\mu &\xrightarrow{U(1)} A_\mu - \frac{1}{e} \partial_\mu \theta(x)
 \end{aligned} \right\}$$

$$\mathcal{L}_{\text{QED}} = \bar{\Psi} (i \gamma^\mu \partial_\mu) \Psi - m \bar{\Psi} \Psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - e \bar{\Psi} \gamma^\mu \Psi A_\mu$$

$$D_\mu \Psi = (\partial_\mu + i e A_\mu) \Psi \xrightarrow{U(1)} e^{i\theta(x)} D_\mu \Psi$$

$$\mathcal{L}_{\text{QED}} = \bar{\Psi} (i \gamma^\mu D_\mu) \Psi - m \bar{\Psi} \Psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

# Eletrodinâmica Quântica (QED)



J.C. Maxwell - 1862

# Grupos de Simetria Não-Abelianos

(isospin)

$$N = \begin{pmatrix} p \\ n \end{pmatrix}_A$$

$$A = 1, 2$$

$$\xrightarrow[\text{GLOBAL}]{SU(2)}$$

$$N' = e^{i\alpha_a \frac{\sigma_{AB}^a}{2}} \begin{pmatrix} p \\ n \end{pmatrix}_B$$

$$a = 1, 2, 3$$

(QCD)

$$q = \begin{pmatrix} q_R \\ q_G \\ q_B \end{pmatrix}_A$$

$$A = 1, 2, 3$$

$$\xrightarrow[\text{LOCAL}]{SU(3)}$$

$$q' = e^{i\alpha_a t_{AB}^a} \begin{pmatrix} q_R \\ q_G \\ q_B \end{pmatrix}_B$$

$$a = 1, \dots, 8$$

# Grupos de Simetria Não-Abelianos

A versão local também exige **bosons de Gauge** (como o fóton para o caso U(1) ):

$$\psi(x) \xrightarrow[\text{LOCAL}]{\text{N-ABEL.}} U(x) \psi(x)$$

$\underbrace{\hspace{10em}}_{\text{EXP}(i\alpha_a t^a)}$

$$D_\mu \equiv d_\mu - i g \underbrace{A_\mu^a}_{\text{MATRIX}} t^a \rightarrow \text{ONE FOR EACH "DIRECTION" (GENERATOR)}$$

$$A_\mu^a = (A_\mu^1, A_\mu^2, A_\mu^3)$$

$$A_\mu^M = \frac{1}{2} \begin{pmatrix} A_\mu^3 & A_\mu^1 - i A_\mu^2 \\ A_\mu^1 + i A_\mu^2 & -A_\mu^3 \end{pmatrix}$$

# Grupos de Simetria Não-Abelianos

A versão local também exige **bosons de Gauge** (como o fóton para o caso U(1)):

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$$D_\nu \equiv d_\nu - i g \underbrace{A_\nu^a}_{\text{MATRIX}} t^a \rightarrow \text{ONE FOR EACH "DIRECTION" (GENERATOR)}$$

$$A_\nu^a = (A_\nu^1, A_\nu^2, A_\nu^3)$$

$$A_\nu^M = \frac{1}{2} \begin{pmatrix} A_\nu^3 & A_\nu^1 - i A_\nu^2 \\ A_\nu^1 + i A_\nu^2 & -A_\nu^3 \end{pmatrix}$$

$$A_\nu^a t^a \xrightarrow[\text{LOCAL}]{\tilde{N}\text{-ABEL.}} U(x) \cdot A_\nu^a t^a \cdot U^\dagger(x) = \left( A_\nu^a + \frac{1}{g} (d_\nu \alpha^a) + f_{abc} A_\nu^b \alpha^c \right) t^a + O(\alpha^2)$$

# Grupos de Simetria Não-Abelianos

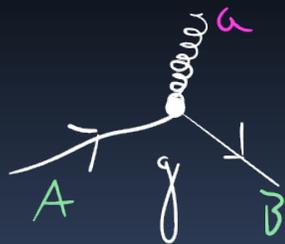
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$$\Psi(x) \xrightarrow[\text{LOCAL}]{\tilde{N}\text{-ABEL.}} U(x) \Psi(x)$$

$\hookrightarrow \text{EXP}(i\alpha_a t^a)$

$$A_\mu^a t^a \xrightarrow[\text{LOCAL}]{\tilde{N}\text{-ABEL.}} U(x) \cdot A_\mu^a t^a \cdot U^\dagger(x) = \left( A_\mu^a + \frac{1}{g} (d_\mu \alpha^a) + f^{abc} A_\mu^b \alpha^c \right) t^a + \mathcal{O}(\alpha^2)$$

$$\mathcal{L}_{YM} = \underbrace{\bar{\Psi} (i \not{D} - m) \Psi}_{\text{fermion}} - \underbrace{\frac{1}{4} (F_{\mu\nu}^a)^2}_{\text{gauge}} \rightarrow F_{\mu\nu}^a \equiv \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g f^{abc} A_\mu^b A_\nu^c$$



# Grupos de Simetria Não-Abelianos

A versão local também exige **bosons de Gauge** (como o fóton para o caso U(1)):

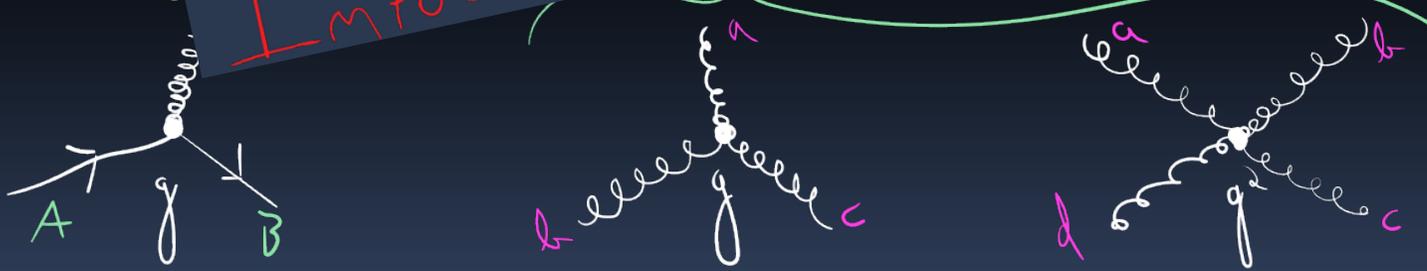
$$\Psi(x) \xrightarrow[\text{LOCAL}]{\tilde{N}\text{-ABEL.}} U(x) \Psi(x)$$

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$$\mathcal{L}_m = \bar{\Psi} (i \not{D} - m) \Psi - \frac{1}{4} F_{\mu\nu}^a F^{\mu\nu a} + g \bar{\Psi} \gamma^\mu T^a \Psi A_\mu^a + g f^{abc} A_\mu^b A_\nu^c \partial_\mu A_\nu^a$$

**IMPORTANT POINT:**  $m^2 A_\mu^a A_\nu^a$   
 $\partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g f^{abc} A_\mu^b A_\nu^c$



# Cromodinâmica Quântica (QCD)



Quarks

Qual força os mantém unidos?

1963



G. Zweig



M. Gell-Mann

Simetria Local: **SU(3)**

1965



Y. Nambu



M-Y Han



O.W. Greenberg

Têm cargas de SU(3)

**u**  
up

**d**  
down

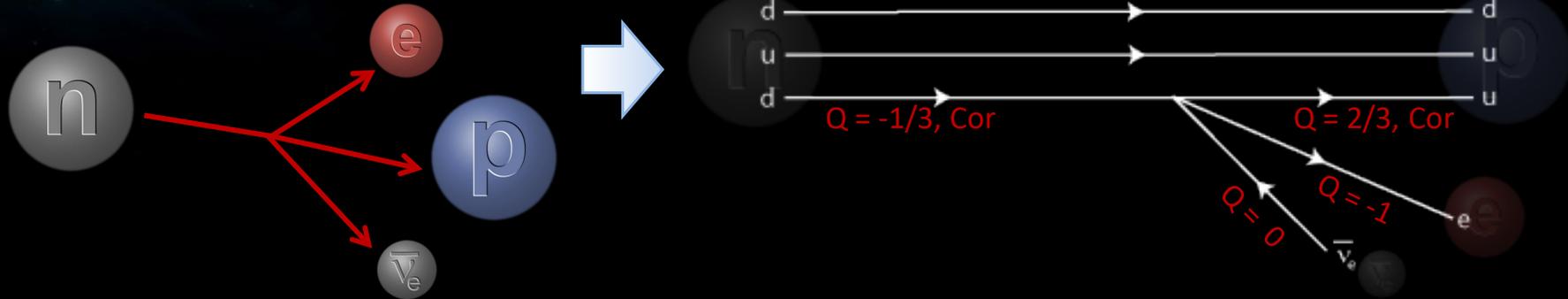
**s**  
strange

Bóson de Gauge  
de SU(3)

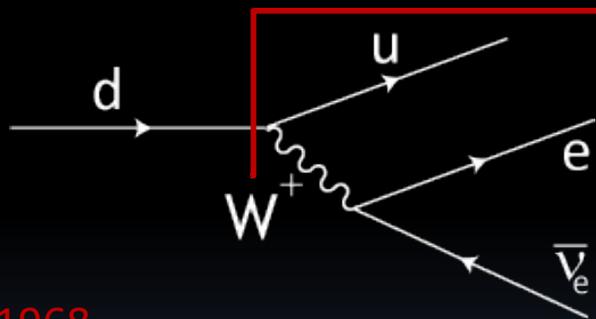
**g**  
gluon

# Teoria Eletrofraca (GWS)

Decaimento Beta:



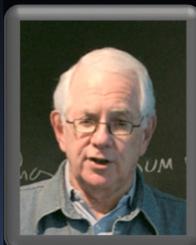
Simetria Local:  $SU(2)_L \times U(1)_Y$



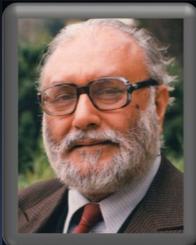
Bósons de Gauge de  $SU(2)_L \times U(1)_Y$



1968



Glashow



Salan



Weinberg

A MODEL OF LEPTONS\*  
 Steven Weinberg†  
 Laboratory for Nuclear Science and Physics Department,  
 Massachusetts Institute of Technology, Cambridge, Massachusetts  
 (Received 17 October 1967)

# Teoria Eletrofraca (GWS)

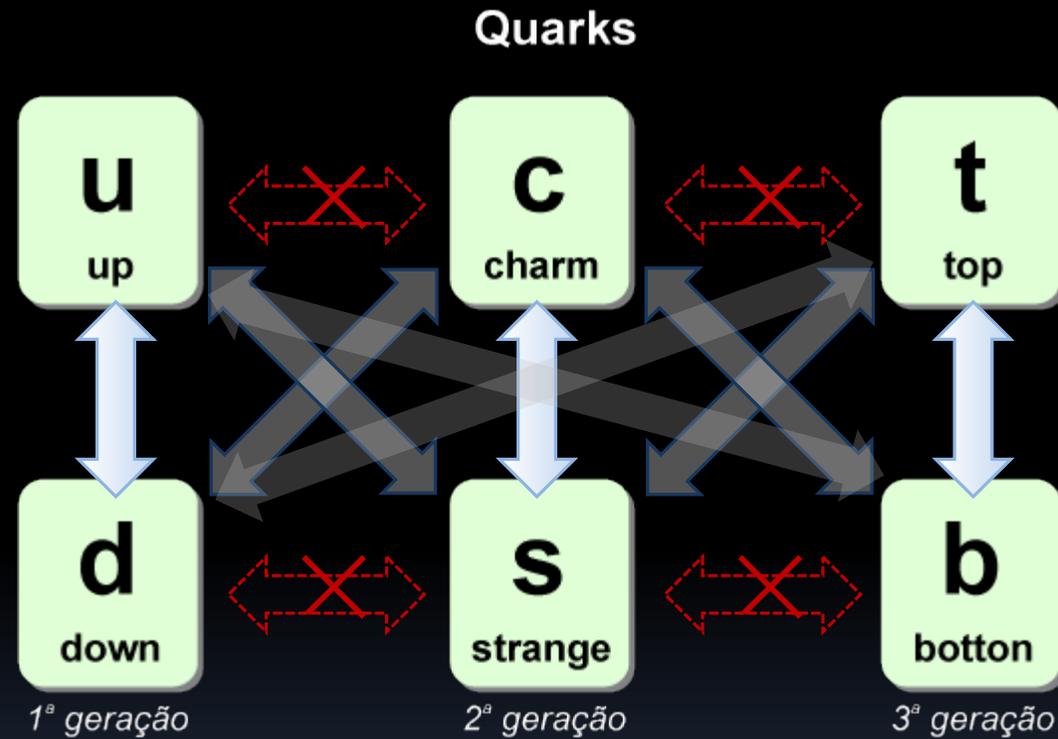
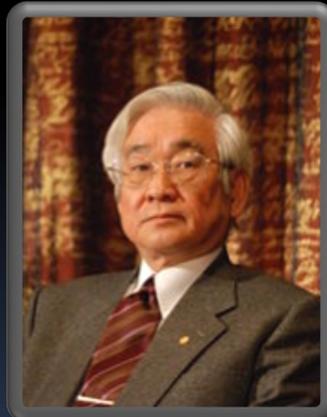


**Matriz CKM (1973)**

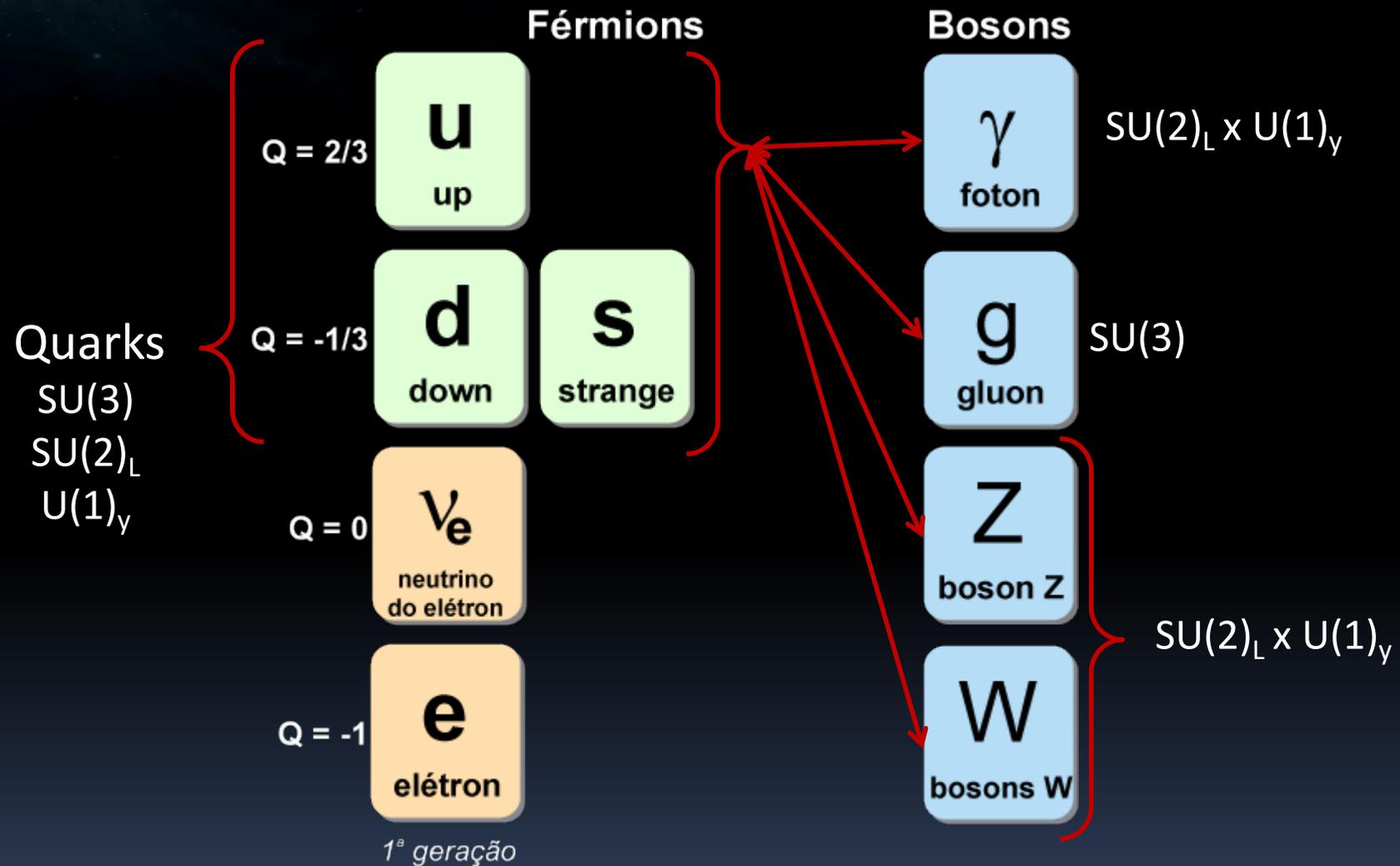
M. Kobayashi



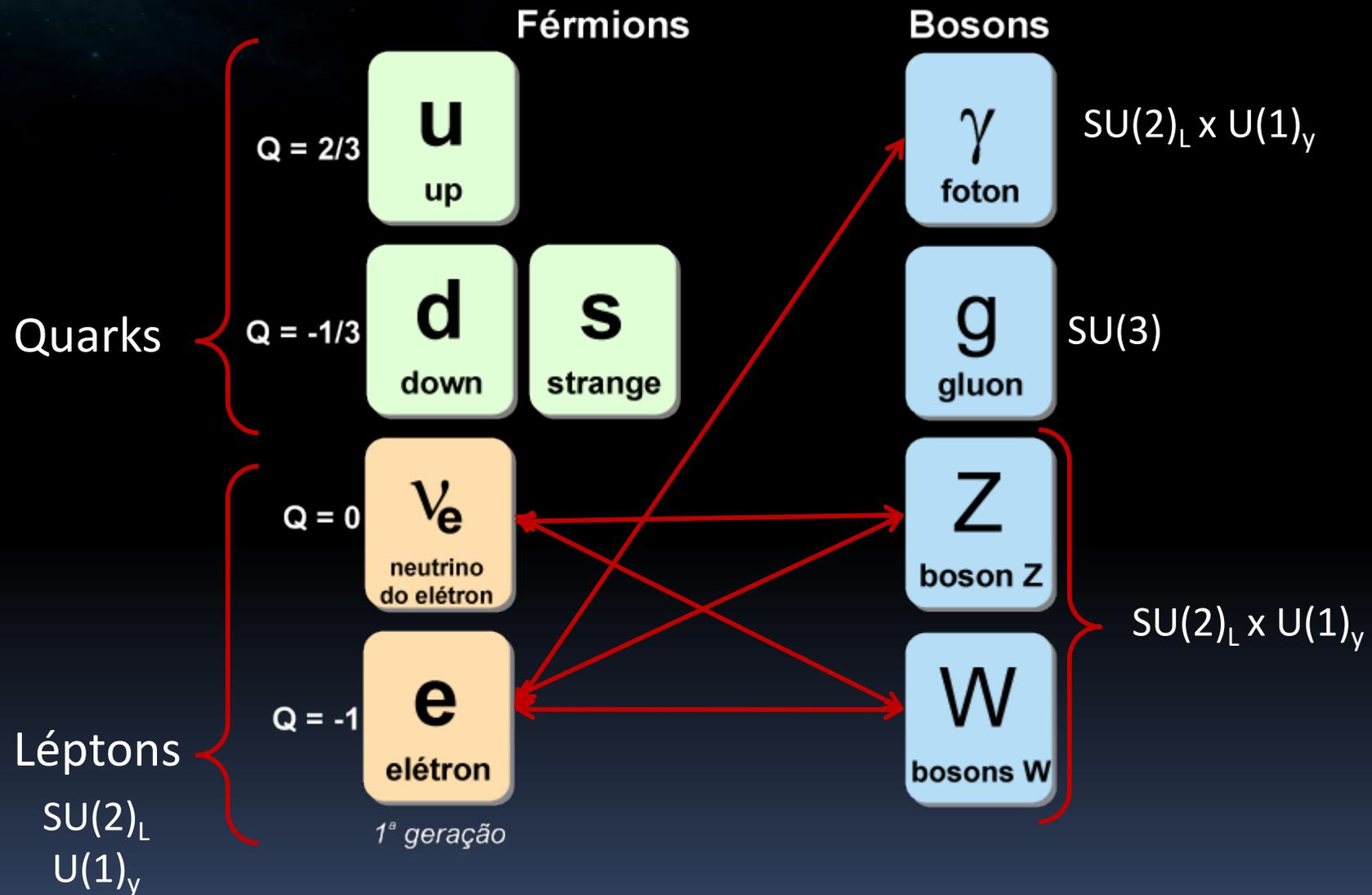
T. Maskawa



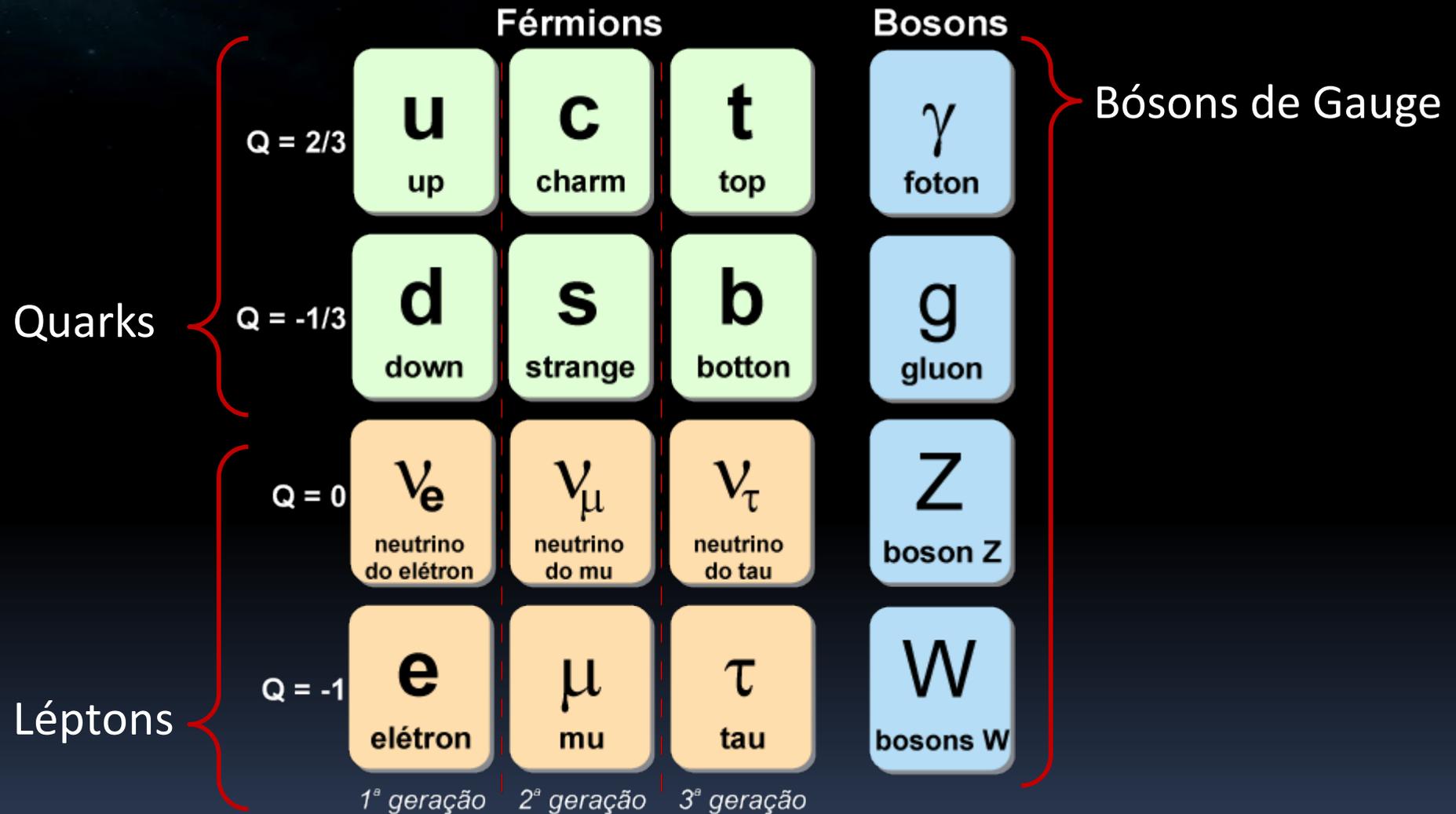
# O Modelo Padrão



# O Modelo Padrão



# O Modelo Padrão



# O Modelo Padrão

**Isso é tudo então? Podemos ir para casa?**

Bem, vamos lembrar de um fato:



“Excitações do campo de interação (Bósons de Gauge) **NÃO TÊM MASSA**”

**... vamos dar uma olhada.**

Quarks

$Q = -1/3$

d  
down

s  
strange

b  
bottom

g  
gluon

$Q = 0$

$\nu_e$   
neutrino do elétron

$\nu_\mu$   
neutrino do mu

$\nu_\tau$   
neutrino do tau

Z  
boson Z

Léptons

$Q = -1$

e  
elétron

$\mu$   
mu

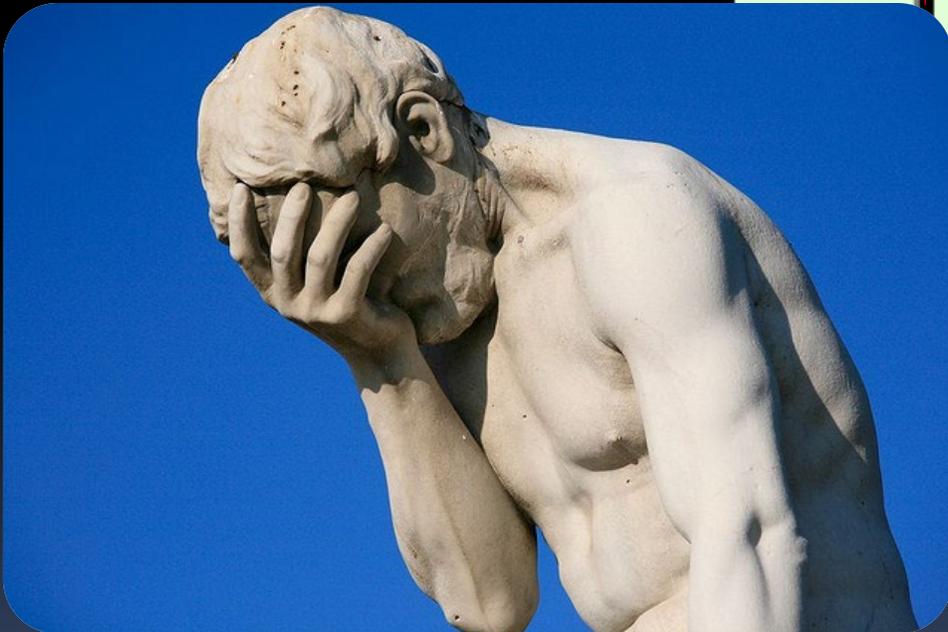
$\tau$   
tau

W  
bosons W

1ª geração 2ª geração 3ª geração

# O Modelo Padrão

	Férmions			Bosons	
$Q = 2/3$	<b>u</b> up	<b>c</b> charm	<b>t</b> top	$\gamma$ foton	$m = 0$ ✓
$Q = -1/3$	<b>d</b>	<b>s</b> strange	<b>b</b> botton	<b>g</b> gluon	$m = 0$ ✓
		$\nu_{\mu}$ neutrino do mu	$\nu_{\tau}$ neutrino do tau	<b>Z</b> boson Z	$m = 92 \text{ GeV}$ ✗
		$\mu$ mu	$\tau$ tau	<b>W</b> bosons W	$m = 80 \text{ GeV}$ ✗
		2ª geração	3ª geração		



# O Modelo Padrão

**Isso é tudo então? Podemos ir para casa?**

Bem, vamos lembrar de um fato:

“Excitações do campo de interação (Bósons de Gauge) **NÃO TÊM MASSA**”

**Os bósons W e Z têm todas as propriedades previstas pela simetria  $SU(2)_L \times U(1)_Y$ , mas eles têm **MASSA****

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**E não é só isso:** a simetria  $SU(2)_L$  proíbe que os **férmions** tenham massa também! Vamos ver...

$$\Psi = \underbrace{P_L \Psi}_{\Psi_L} + \underbrace{P_R \Psi}_{\Psi_R}$$

$$m \overline{\Psi} \Psi = m (\overline{\Psi}_L \Psi_R + \overline{\Psi}_R \Psi_L)$$

$\underbrace{\hspace{10em}}$   
**MASS BASIS** **CHIRALITY BASIS**

# O Modelo Padrão

**Isso é tudo então? Podemos ir para casa?**

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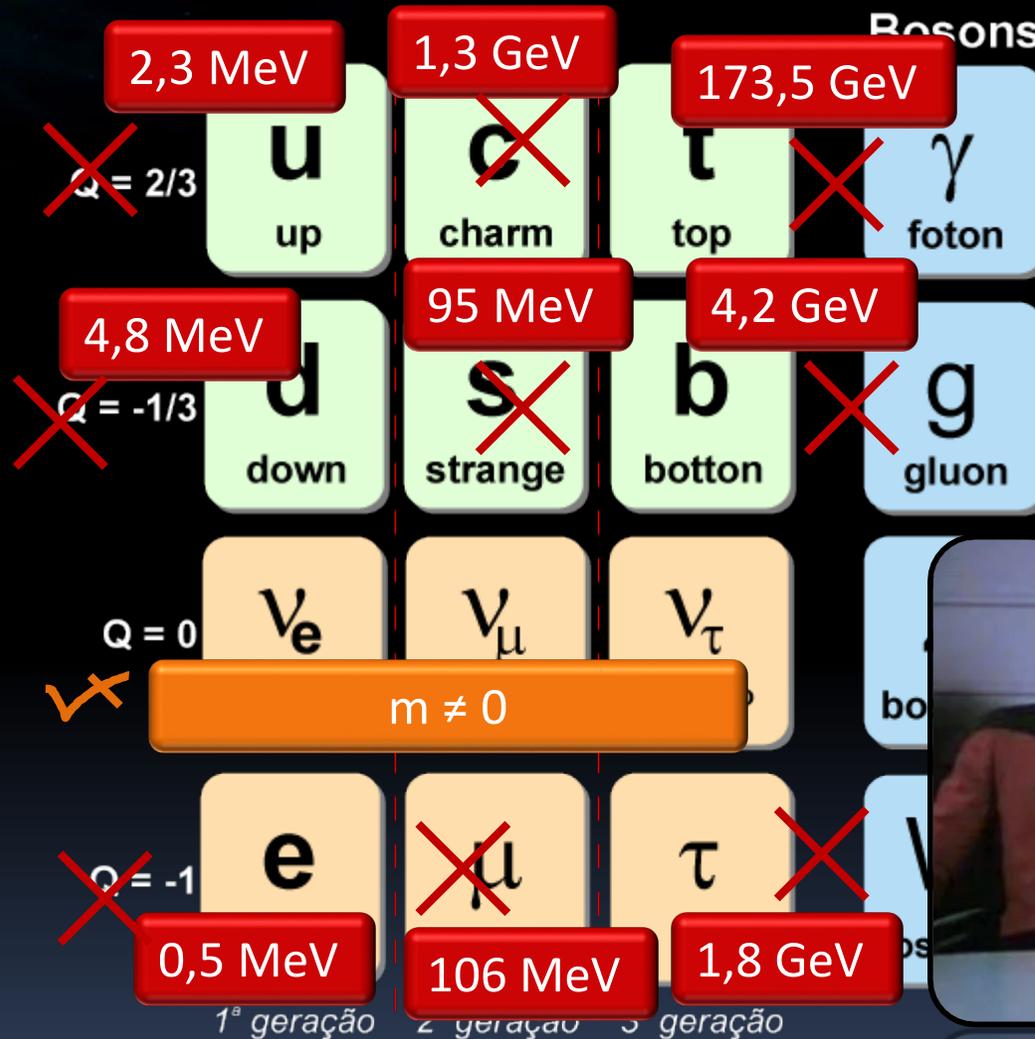
$$\Psi = \underbrace{P_L \Psi}_{\Psi_L} + \underbrace{P_R \Psi}_{\Psi_R}$$

$$m \cancel{\bar{\Psi} \Psi} = m (\cancel{\bar{\Psi}_L \Psi_R} + \cancel{\bar{\Psi}_R \Psi_L})$$

$$\Psi_L \xrightarrow{SU(2)_L} e^{i \frac{g_a}{2} \theta_a^{(r)}} \Psi_L = e^{i t_a \theta_a} \Psi_L$$

$$\Psi_R \xrightarrow{SU(2)_L} \Psi_R$$

# O Modelo Padrão



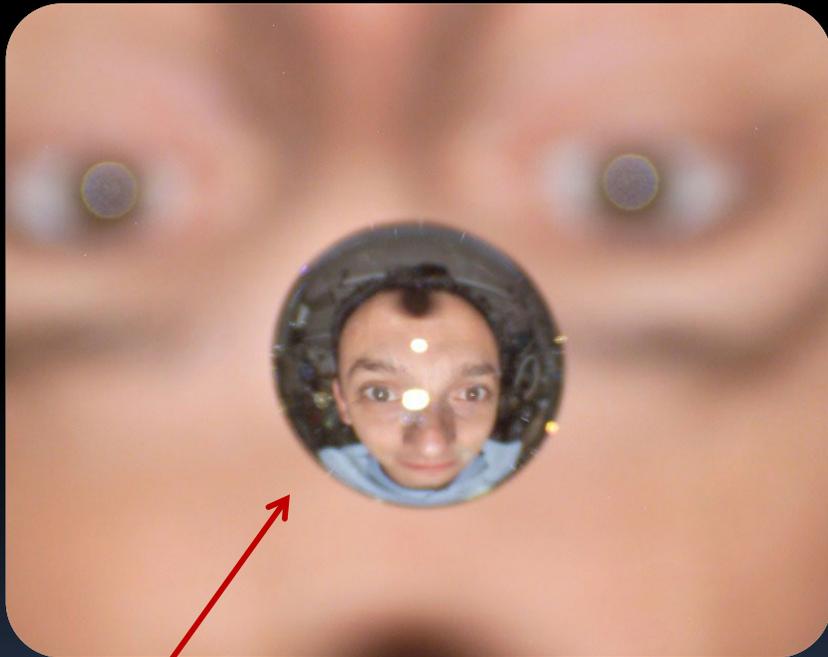
# O Bóson de Higgs

**Dilema:** As simetrias funcionam! **VS** Uma delas proíbe a massa!

# O Bóson de Higgs

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Quebra espontânea de simetria:

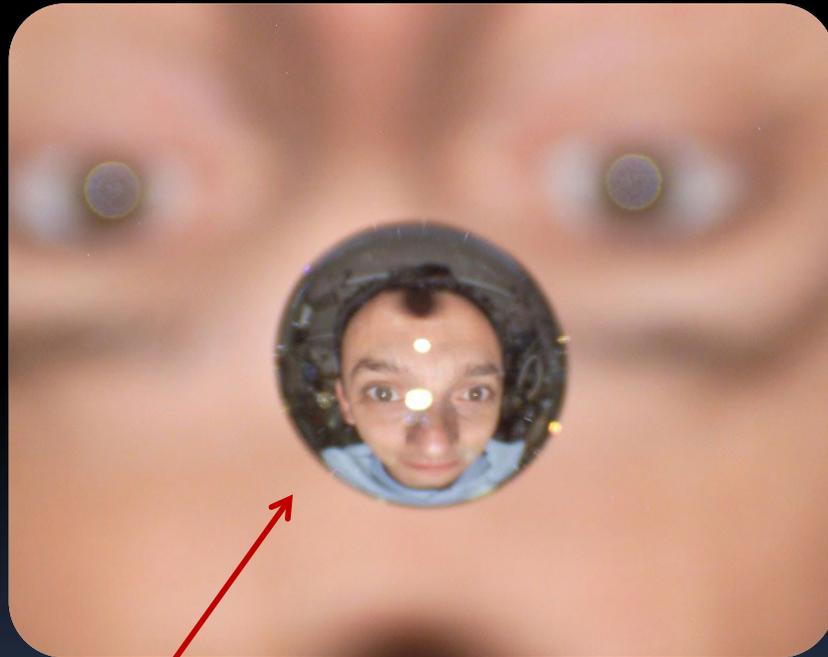


Gota de água (no espaço)

# O Bóson de Higgs

**Dilema:** As simetrias funcionam! **VS** Uma delas proíbe a massa!

Quebra espontânea de simetria:



Gota de água (no espaço)

Frio  
→  
(abaixo a energia do sistema)

Simetria rotacional “menor”



Mas de fato **PERDEMOS** a simetria?

# O Bóson de Higgs

**Dilema:** As simetrias funcionam! **VS** Uma delas proíbe a massa!

Mas de fato **PERDEMOS** a simetria?



Frio  
→  
(abaixo a energia do sistema)



**NÃO!** Ela apenas está se manifestando de uma forma mais sutil

# O Bóson de Higgs

Quebra espontânea de simetria: um exemplo de  $SO(2)$

$$\phi^2 = \phi_1^2 + \phi_2^2$$

$$\phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$

$$\mathcal{L} = \frac{1}{2} (\partial_\nu \phi^i)(\partial^\nu \phi^i) - V(\underbrace{\phi \cdot \phi})$$

# O Bóson de Higgs

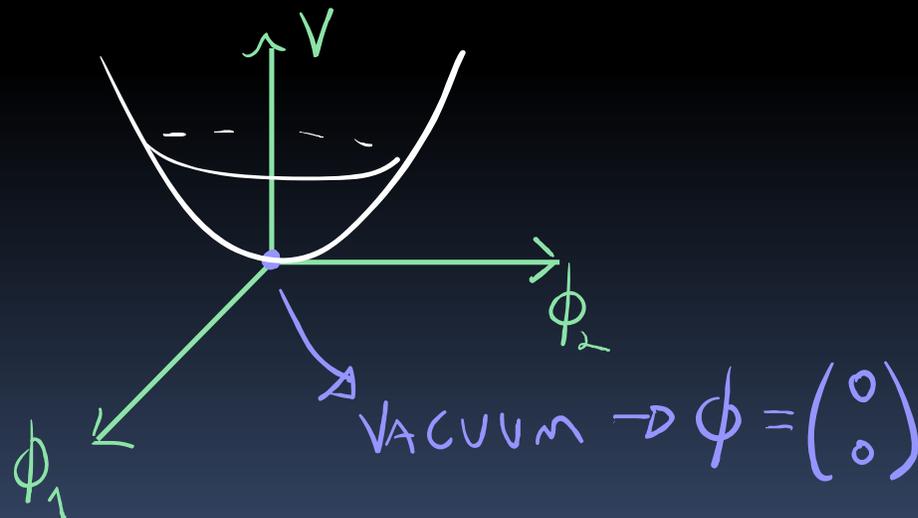
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$$V(\phi^2) = \frac{1}{2} \mu^2 \phi^2 + \frac{\lambda}{4} (\phi^2)^2$$



# O Bóson de Higgs

Quebra espontânea de simetria: um exemplo de  $SO(2)$

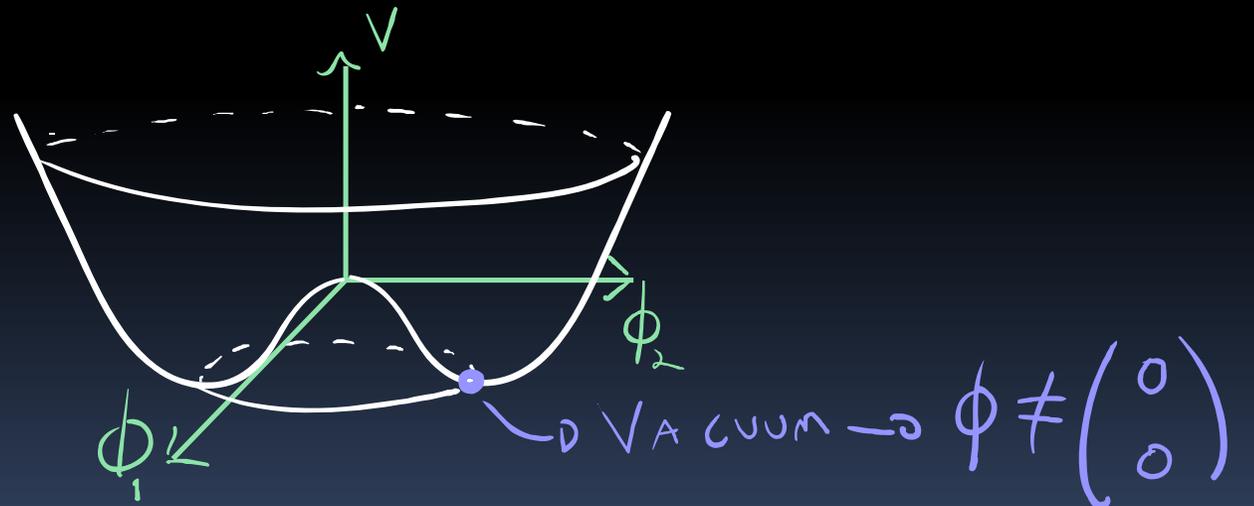
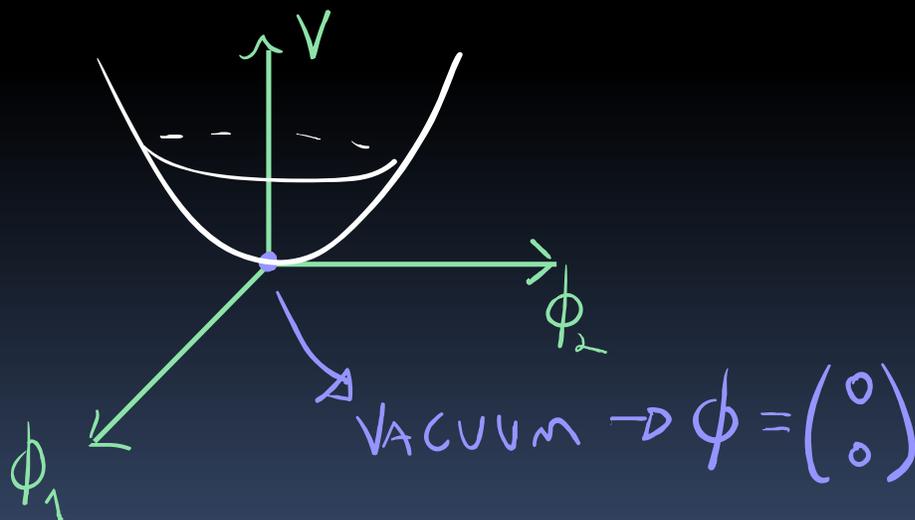
$$\phi^2 = \phi_1^2 + \phi_2^2$$

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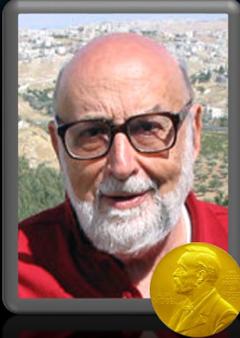
$$V(\phi^2) = \frac{1}{2} \mu^2 \phi^2 + \frac{\lambda}{4} (\phi^2)^2$$

$$V(\phi^2) = -\frac{1}{2} \mu^2 \phi^2 + \frac{\lambda}{4} (\phi^2)^2$$



# O Bóson de Higgs

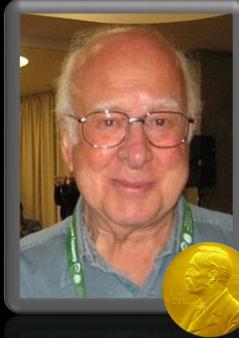
Englert



Brout



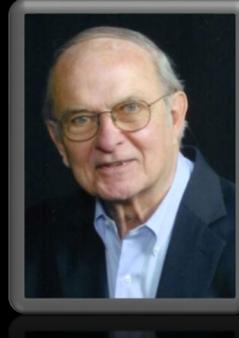
Higgs



Guralnik



Hagen



Kibble



1964

Campo escalar:



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

Estado de menor energia (vácuo), não respeita a simetria

# O Bóson de Higgs

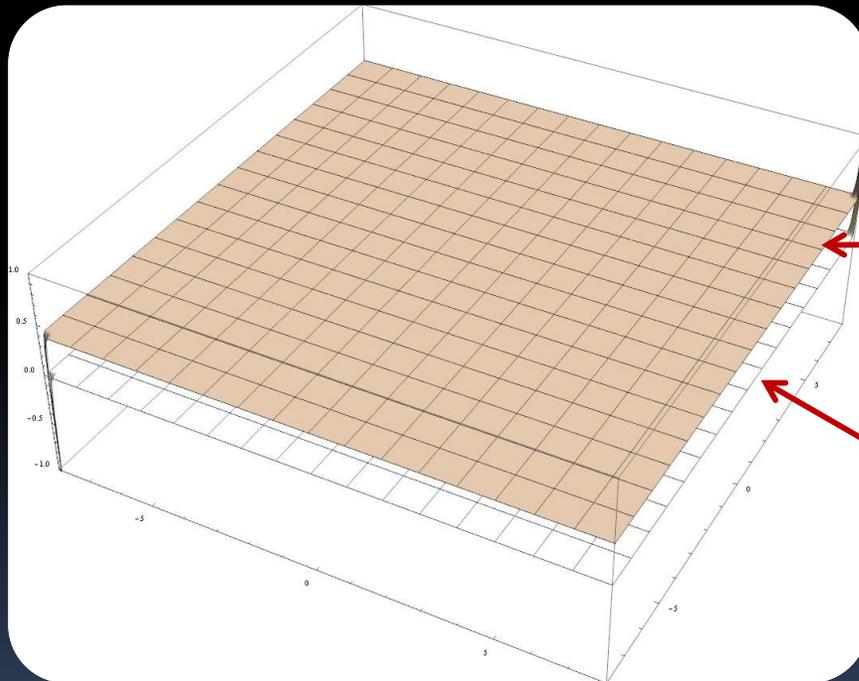
Campo escalar:



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

Estado de menor energia (vácuo), não respeita a simetria

**Efeito:** Valor esperado no vácuo (**VEV**)!



Nenhuma partícula aqui

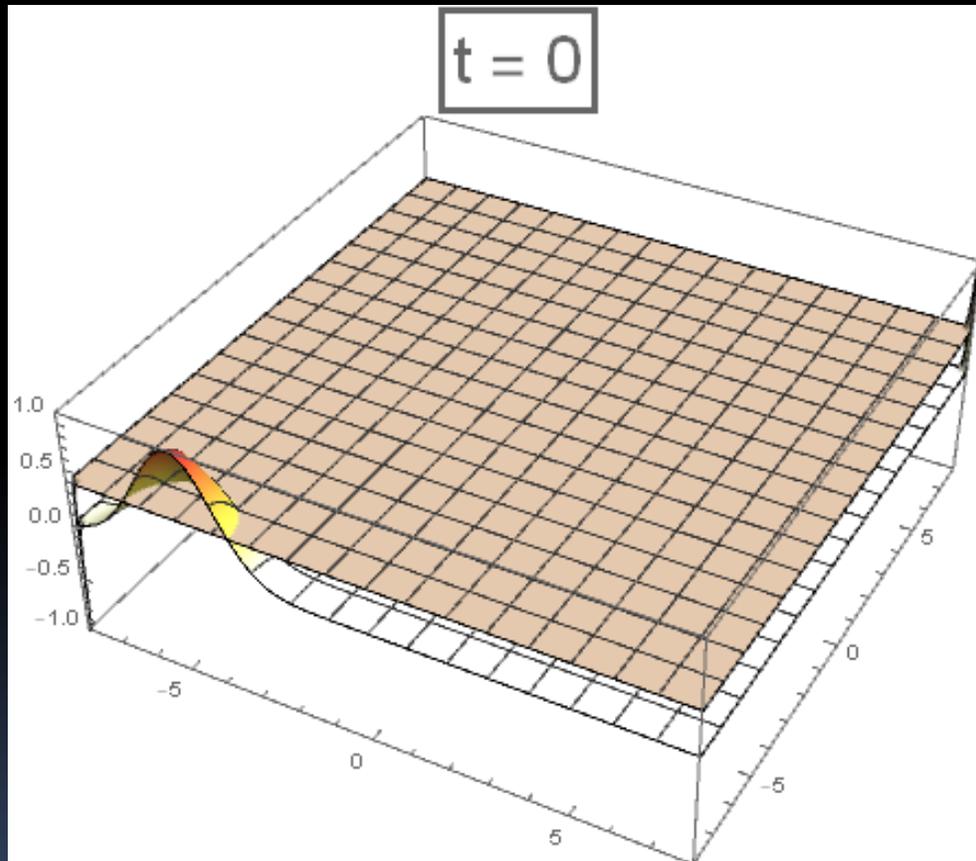
Vácuo do campo H  
(246 GeV)

Vácuo normal

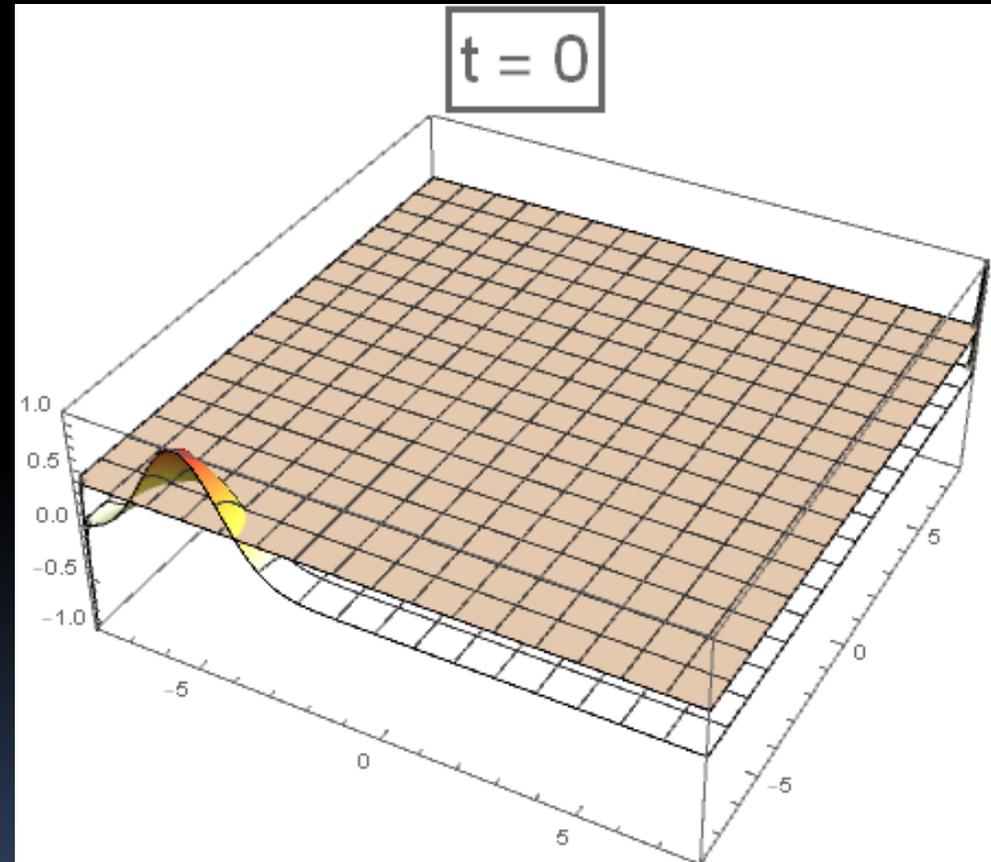
# O Bóson de Higgs

Qualquer campo que interaja com o campo H vai sentir este VEV

Não Interage



Interage



# O Bóson de Higgs

$$\mathcal{L}_{H\Psi} = \underbrace{-y_\Psi \bar{\Psi}_L H \Psi_R}_{\text{YUKAWA COUPLING}} \xrightarrow{SU(2)_L \times U(1)_Y} -y_\Psi \bar{\Psi}_L e^{-i t_a \theta_a - i(\gamma_L - \gamma_R - \gamma_H)\Theta + i t_a \theta_a} H \Psi_R$$

# O Bóson de Higgs

$$\mathcal{L}_{H\psi} = \underbrace{-y_\psi \bar{\Psi}_L H \Psi_R}_{\text{YUKAWA COUPLING}} \xrightarrow{SU(2)_L \times U(1)_Y} -y_\psi \bar{\Psi}_L e^{-i t_a \theta_a - i(\gamma_L - \gamma_R - \gamma_H)\Theta + i t_a \theta_a} H \Psi_R$$

$$H \rightarrow \frac{1}{\sqrt{2}}(h + i\sigma)$$

$$v = 246 \text{ GeV}$$

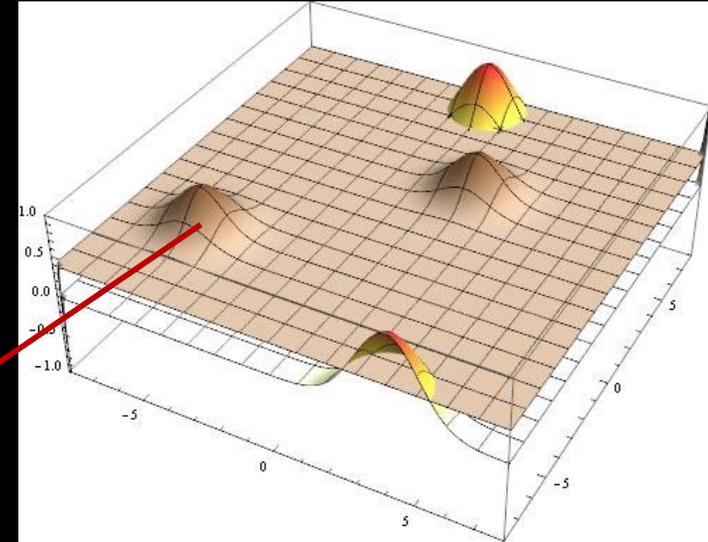
$$\mathcal{L}_{H\psi} = \underbrace{-\frac{y_\psi v}{\sqrt{2}} \bar{\Psi}_L \Psi_R}_{m_\psi} - \frac{y_\psi}{\sqrt{2}} \bar{\Psi}_L \Psi_R h$$


# O Bóson de Higgs

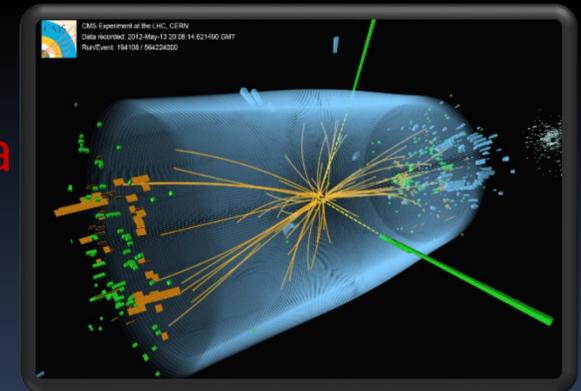
Teoria  
1968

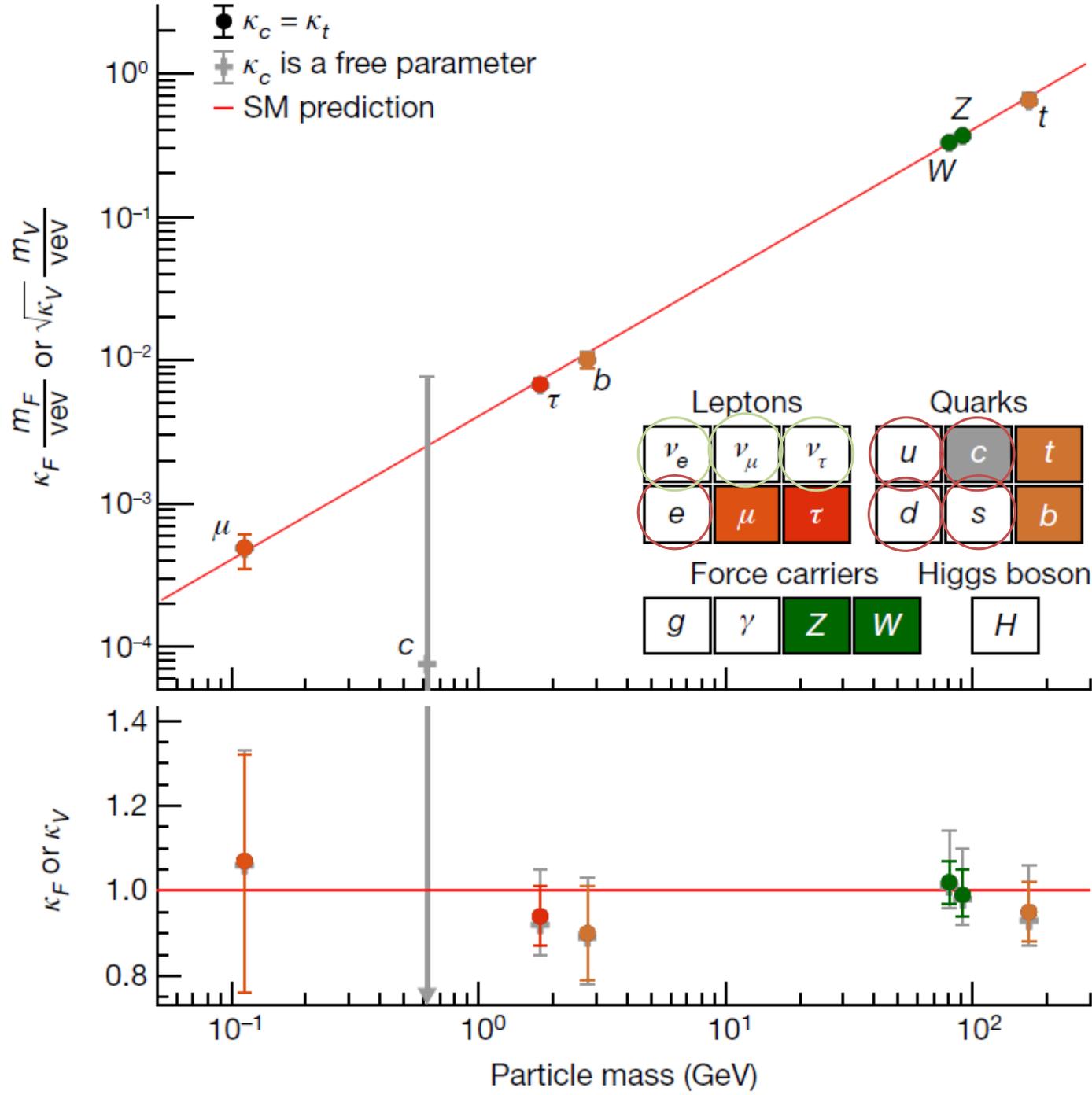
	Férmions			Bosons
Q = 2/3	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>γ</b> foton
Q = -1/3	<b>d</b> down	<b>s</b> strange	<b>b</b> botton	<b>g</b> gluon
Q = 0	<b>ν<sub>e</sub></b> neutrino do elétron	<b>ν<sub>μ</sub></b> neutrino do mu	<b>ν<sub>τ</sub></b> neutrino do tau	<b>Z</b> boson Z
Q = -1	<b>e</b> elétron	<b>μ</b> mu	<b>τ</b> tau	<b>W</b> bosons W
	1ª geração	2ª geração	3ª geração	

**h**  
boson de Higgs



Experiência  
2012





Untested!  
Who knows?!

ATLAS Collaboration, Nature 607 (2022) 7917, 52-59,  
Nature 612 (2022) 7941, E24 (erratum)



# OPEN PROBLEMS

- Fermion masses?

$$\mathcal{L}_H = m_d \bar{d}_L d_R + h.c.$$

$$m_d = \frac{Y_d v}{\sqrt{2}}$$

$$v \approx 246 \text{ GeV}$$

$$Y_e \sim 10^{-5}$$

$$Y_u \approx Y_d \sim 10^{-3}$$

No idea of how!  $Y_t \sim 1$

Are neutrinos also getting mass the same way?

- Dark matter?
- CP violation? (Big enough to do Baryogenesis?) Strong phase transitions?
- Hierarchy of scales and fine tunings: Higgs mass, cosmological constant, strong CP?

# OPEN PROBLEMS

$m_e$	Electron mass	511 keV
$m_\mu$	Muon mass	105.7 MeV
$m_t$	Tau mass	1.78 GeV
$m_u$	Up quark mass	1.9 MeV
$m_d$	Down quark mass	4.4 MeV
$m_s$	Strange quark mass	87 MeV
$m_c$	Charm quark mass	1.32 GeV
$m_b$	Bottom quark mass	4.24 GeV
$m_t$	Top quark mass	173.5 GeV
$\theta_{12}$	CKM 12-mixing angle	13.1°
$\theta_{23}$	CKM 23-mixing angle	2.4°
$\theta_{13}$	CKM 13-mixing angle	0.2°
$\delta$	CKM CP violation Phase	0.995
$g'$	U(1) gauge coupling	0.357
$g$	SU(2) gauge coupling	0.652
$g_s$	SU(3) gauge coupling	1.221
$\theta_{QCD}$	QCD vacuum angle	$\sim 0$
$v$	Higgs vacuum expectation value	246 GeV
$m_H$	Higgs mass	125.09 ± 0.24 GeV

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# OPEN PROBLEMS

$m_e$	Electron mass	511 keV
$m_\mu$	Muon mass	105.7 MeV
$m_t$	Tau mass	1.78 GeV
$m_u$	Up quark mass	1.9 MeV
$m_d$	Down quark mass	4.4 MeV
$m_s$	Strange quark mass	87 MeV
$m_c$	Charm quark mass	1.32 GeV
$m_b$	Bottom quark mass	4.24 GeV
$m_t$	Top quark mass	173.5 GeV
$\theta_{12}$	CKM 12-mixing angle	13.1°
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All of these are equivalent to fixing Yukawa couplings, in total we have 13 parameters (12 modules and 1 complex phase)

This is the **majority** of the 19 parameters of the standard model!

If you include **neutrinos** as Dirac fermions, you get an extra 7 parameters, all equivalent to Yukawa couplings

# Obrigado pela atenção!

Mais recursos online

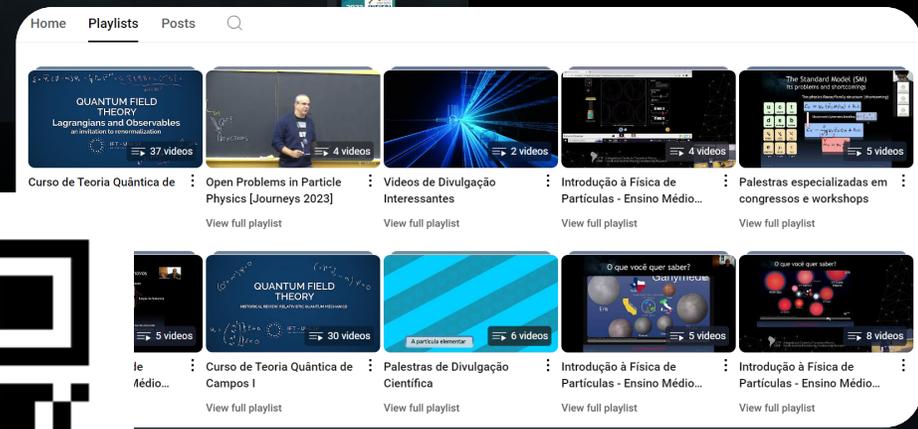
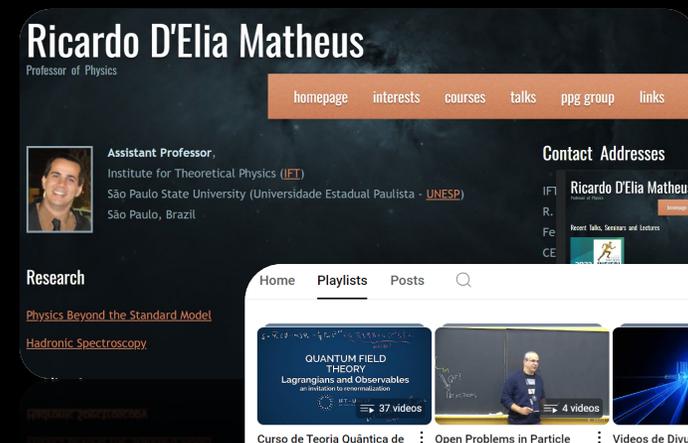
Meu site:



<https://professores.ift.unesp.br/ricardo.matheus/>

<https://www.youtube.com/@ricardomatheus>

Playlists no Youtube:







# Quantização de uma teoria ñ-relativística

$$\rho(\vec{x}, t) = |\Psi(\vec{x}, t)|^2$$

$$i \frac{\partial}{\partial t} \Psi(x, t) = -\frac{1}{2m} \nabla^2 \Psi(x, t)$$

$$\frac{\partial \rho}{\partial t} = -\vec{\nabla} \cdot \vec{j}(\vec{x}, t)$$

$$\vec{j}(\vec{x}, t) = -\frac{i}{2m} [\Psi^* \vec{\nabla} \Psi - \Psi \vec{\nabla} \Psi^*]$$



$$\frac{d}{dt} \iiint \rho \, dV = - \oiint (\vec{j} \cdot \hat{n}) \, dS$$

# Quantização de uma teoria relativística

$$-\frac{\partial^2}{\partial t^2} \psi(\vec{x}, t) = -\nabla^2 \psi(\vec{x}, t) + m^2 \psi(\vec{x}, t) \quad / \quad \psi(\vec{x}, t) = N e^{i\vec{p}\cdot\vec{x} - iEt}$$

$$\frac{\partial \mathcal{P}}{\partial t} = -\vec{\nabla} \cdot \vec{j}(\vec{x}, t) \quad \longleftrightarrow \quad \mathcal{P} = i \left( \psi^* \frac{\partial}{\partial t} \psi - \psi \frac{\partial}{\partial t} \psi^* \right)$$

$$\mathcal{P} = i \left( \psi^* \frac{\partial}{\partial t} \psi - \psi \frac{\partial}{\partial t} \psi^* \right) = 2E |N|^2 \left. \begin{array}{l} \\ E = \pm \sqrt{p^2 + m^2} \end{array} \right\} \begin{array}{l} \text{Energia e densidade de prob.} \\ \text{negativas!} \end{array}$$

# Quantização (quadro de Heis.)

Clássico

$$\dot{x} = \{x, H\}_{PB} = \frac{\partial H}{\partial p}$$

$$\dot{p} = \{p, H\}_{PB} = -\frac{\partial H}{\partial x}$$

Quântico

$$\frac{d\hat{x}}{dt} = -\frac{i}{\hbar} [\hat{x}, \hat{H}]$$

$$\frac{d\hat{p}}{dt} = -\frac{i}{\hbar} [\hat{p}, \hat{H}]$$