

Modelo Padrão e Bóson(s) de Higgs

Ronaldo Thibes
DEBI / UESB

Itapetinga, agosto de 2012

1

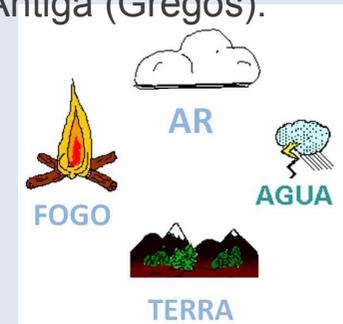
Física de Partículas Elementares

- Pergunta Principal:

De que são feitas as coisas?
(ao nível mais fundamental)

- Resposta Antiga (Gregos):

- Ar
- Água
- Fogo
- Terra



Demócrito:

á t o m o

2

Física de Partículas Elementares

- Pergunta Principal:

De que são feitas as coisas?
(ao nível mais fundamental)

- Referencial Teórico

| | |
|------------------------|---------------------------|
| Mecânica Clássica | Mecânica Quântica |
| Mecânica Relativística | Teoria Quântica de Campos |

5

Referenciais Teóricos

| | |
|------------------------|---------------------------|
| Mecânica Clássica | Mecânica Quântica |
| Mecânica Relativística | Teoria Quântica de Campos |

- Princípios Gerais

- Mecânica Clássica → conservação da massa
- Mecânica Relativística → invariância de Lorentz
- Mecânica Quântica → princípio da exc. de Pauli (*ad hoc*)
- Teoria Quântica de Campos → teorema da exc. de Pauli (*provado*) – criação de parts.

6

Interações Fundamentais

- QED (Quantum Electrodynamics – eletromagnetismo)
- Interações Fracas (força fraca – decaimento beta)
- QCD (Quantum Chromodynamics – força forte)
- Força Gravitacional

Força fraca + eletromagnetismo



Unificadas na Teoria Eletrofraca
SU(2) x U(1)

7

Modelo Padrão

- QED
 - Interações Fracas
 - QCD
- } => Modelo Padrão (Standard Model)

Grupos de Simetria Local:

U(1) x SU(2) → t. eletrofraca

SU(3) → QCD

| | | | | |
|---------|---|---|--|---|
| | 2.4 MeV/c ² 2/3 1/2 u up | 1.27 GeV/c ² 2/3 1/2 c charm | 171.2 GeV/c ² 2/3 1/2 t top | 0 0 1 γ photon |
| Quarks | 4.8 MeV/c ² -1/3 1/2 d down | 104 MeV/c ² -1/3 1/2 s strange | 4.2 GeV/c ² -1/3 1/2 b bottom | 0 0 1 g gluon |
| | <2.2 eV/c ² 0 1/2 ν _e electron neutrino | <0.17 MeV/c ² 0 1/2 ν _μ muon neutrino | <15.5 MeV/c ² 0 1/2 ν _τ tau neutrino | 91.2 GeV/c ² 0 1 Z ⁰ Z boson |
| Leptons | 0.511 MeV/c ² -1 1/2 e electron | 105.7 MeV/c ² -1 1/2 μ muon | 1.777 GeV/c ² -1 1/2 τ tau | 80.4 GeV/c ² -1 1 W [±] W boson |
| | | | | Gauge bosons |

8

Física de Altas Energias

- Produção de Partículas Elementares
 - Raios cósmicos
 - Desintegrações nucleares
 - Aceleradores de partículas
- Por que altas energias?
 - Quanto maior a massa da partícula a ser produzida, maior a necessidade de energia.
 - Quanto maior a energia, mais próximo as partículas chegam entre si.

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9

Tevatron / Fermilab



Localização: Batavia, Illinois, US
Energia Máxima: 1 Tev Circunferência: 6,28 km
Funcionamento: 1983-2011

10

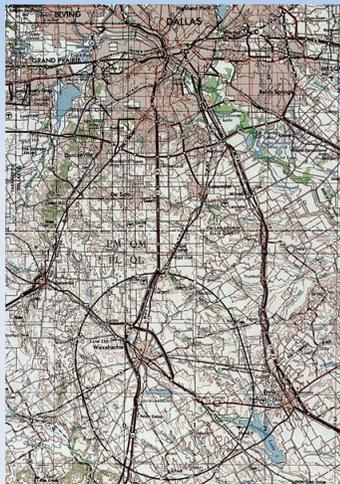
Superconducting Super Collider

Não saiu do papel.
Projeto encerrado em
1993.

Alcançaria energias de
até 40 Tev

Circunferência
planejada: 87,1 km

Waxahachie, Texas



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11

Large Hadron Collider (LHC)

Localização:
CERN (Suiça)

Construção:
1998-2008

Circunferência:
27 km

Energia:
7 Tev



Organisation Européenne pour la Recherche Nucléaire

12

Large Hadron Collider (LHC)



7 experimentos: ALICE, ATLAS, CMS, TOTEM, LHCb, LHCf e MoEDAL

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13

Era Pré Física de Partículas

- 1897: descoberta do elétron (Thomson)
- 1919: descoberta do próton (Rutherford)
- 1932: descoberta do neutron (Chadwick)

- Fóton → radiação corpo negro, efeito fotoelétrico, espalhamento Compton (o nome fóton foi sugerido pelo químico Gilberto Lewis em 1926)

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14

Proliferação de Partículas

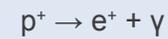
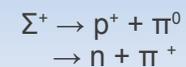
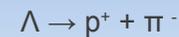
- Partículas Estranhas (Strange)(1945 – 1950)
 $K^0, K^+, K^-, \eta, \Phi, \omega, \rho, \dots$ (instáveis $\sim 10^{-10}$ s)
- Bárion mais leve \rightarrow próton ($\sim 10^{29}$ anos)



- Até 1960: caos de partículas
int. forte \rightarrow bárions e mésons

15

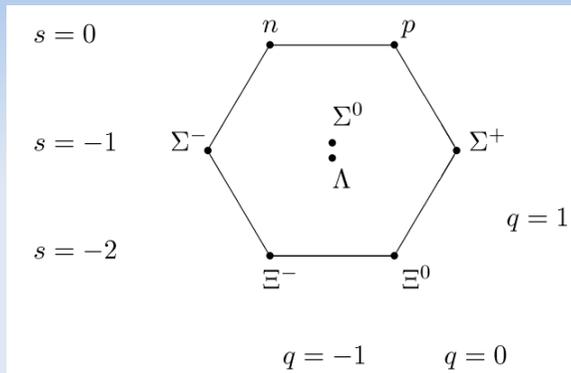
Proliferação de Partículas



- Até 1960: caos de partículas
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16

The Eight-fold Way (1961-1964)

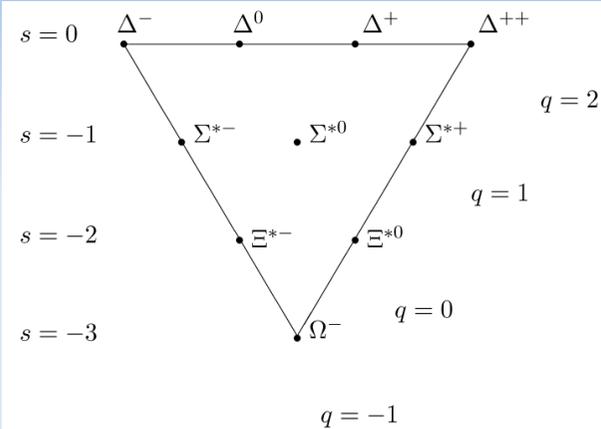


Murray Gell-Mann
(1929, New York)
Nobel Prize 1969

quark

17

The Eight-fold Way (1961-1964)



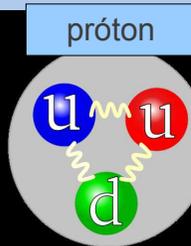
Murray Gell-Mann
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Nobel Prize 1969

quark

18

Modelo de Quarks

| Generation | Name | Symbol | Mass (MeV/c ²) | Charge |
|------------|--------------------|--------|----------------------------|-----------------|
| First | up | u | 1.5-4* | $+\frac{2}{3}e$ |
| | down | d | 4-8 | $-\frac{1}{3}e$ |
| Second | strange | s | 80-130 | $-\frac{1}{3}e$ |
| | charm | c | $1.15-1.35 \times 10^3$ | $+\frac{2}{3}e$ |
| Third | bottom (or beauty) | b | $4.1-4.9 \times 10^3$ | $-\frac{1}{3}e$ |
| | top (or truth) | t | $1.7-1.9 \times 10^4$ | $+\frac{2}{3}e$ |



Top (1995 - Tevatron)

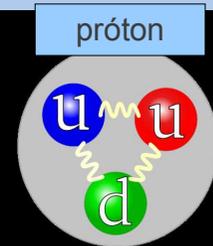
Problema: O modelo de quarks parece violar o princípio da exclusão de Pauli.

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19

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Top (1995 - Tevatron)

Problema: O modelo de quarks parece violar o princípio da exclusão de Pauli.

Solução: Introdução de novo número quântico: **cor**

Somente podem ser observadas partículas colorless

Problema em aberto: **Confinamento de quarks e gluons**

20

Modelo de Quarks

The baryon decuplet

| qqq | Q | S | Baryon |
|-------|-----|-----|---------------|
| uuu | 2 | 0 | Δ^{++} |
| uud | 1 | 0 | Δ^+ |
| udd | 0 | 0 | Δ^0 |
| ddd | -1 | 0 | Δ^- |
| uus | 1 | -1 | Σ^{*+} |
| uds | 0 | -1 | Σ^{*0} |
| dds | -1 | -1 | Σ^{*-} |
| uss | 0 | -2 | Ξ^{*0} |
| dss | -1 | -2 | Ξ^{*-} |
| sss | -1 | -3 | Ω^- |

The meson nonet

| $q\bar{q}$ | Q | S | Meson |
|------------|-----|-----|-------------|
| $u\bar{u}$ | 0 | 0 | π^0 |
| $u\bar{d}$ | 1 | 0 | π^+ |
| $d\bar{u}$ | -1 | 0 | π^- |
| $d\bar{d}$ | 0 | 0 | η |
| $u\bar{s}$ | 1 | 1 | K^+ |
| $d\bar{s}$ | 0 | 1 | K^0 |
| $s\bar{u}$ | -1 | -1 | K^- |
| $s\bar{d}$ | 0 | -1 | \bar{K}^0 |
| $s\bar{s}$ | 0 | 0 | η' |

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Baryons (spin 1/2)

| Baryon | Quark Content | Charge | Mass | Lifetime | Principal Decays |
|--------------------------------------|----------------|--------|--------------------|------------------------|--------------------------------------|
| $N \begin{cases} p \\ n \end{cases}$ | uud udd | 1 0 | 938.272 939.565 | ∞ 885.7 | - $p\bar{\nu}_e$ |
| Λ | uds | 0 | 1115.68 | 2.63×10^{-10} | $p\pi^-, n\pi^0$ |
| Σ^+ | uus | 1 | 1189.37 | 8.02×10^{-11} | $p\pi^0, n\pi^+$ |
| Σ^0 | uds | 0 | 1192.64 | 7.4×10^{-20} | $\Lambda\gamma$ |
| Σ^- | dds | -1 | 1197.45 | 1.48×10^{-10} | $n\pi^-$ |
| Ξ^0 | uss | 0 | 1314.8 | 2.90×10^{-10} | $\Lambda\pi^0$ |
| Ξ^- | dss | -1 | 1321.3 | 1.64×10^{-10} | $\Lambda\pi^-$ |
| Λ_c^+ | udc | 1 | 2286.5 | 2.00×10^{-13} | $pK\pi, \Lambda\pi\pi, \Sigma\pi\pi$ |

Baryons (spin 3/2)

| Baryon | Quark Content | Charge | Mass | Lifetime | Principal Decays |
|------------|----------------------|-------------|------|-----------------------|-------------------------|
| Δ | uuu, uud, udd, ddd | 2, 1, 0, -1 | 1232 | 5.6×10^{-24} | $N\pi$ |
| Σ^* | uus, uds, dds | 1, 0, -1 | 1385 | 1.8×10^{-23} | $\Lambda\pi, \Sigma\pi$ |
| Ξ^* | uss, dss | 0, -1 | 1533 | 6.9×10^{-23} | $\Xi\pi$ |
| Ω^- | sss | -1 | 1672 | 8.2×10^{-11} | $\Lambda K^-, \Xi\pi$ |

Pseudoscalar Mesons (spin 0)

| Meson | Quark Content | Charge | Mass | Lifetime | Principal Decays |
|------------------|--|--------|---------|---|--|
| π^+ | $u\bar{d}, \bar{d}u$ | 1,-1 | 139.570 | 2.60×10^{-8} | $\mu\nu_\mu$ |
| π^0 | $(u\bar{u} - d\bar{d})/\sqrt{2}$ | 0 | 134.977 | 8.4×10^{-17} | $\gamma\gamma$ |
| K^\pm | $u\bar{s}, \bar{s}u$ | 1,-1 | 493.68 | 1.24×10^{-8} | $\mu\nu_\mu, \pi\pi, \pi\pi\pi$ |
| K^0, \bar{K}^0 | $d\bar{s}, s\bar{d}$ | 0 | 497.65 | $\begin{cases} K_S^0: 8.95 \times 10^{-11} \\ K_L^0: 5.11 \times 10^{-8} \end{cases}$ | $\pi\pi$ $\pi e\nu_e, \pi\mu\nu_\mu, \pi\pi\pi$ |
| η | $(u\bar{u} + d\bar{d} - 2s\bar{s})/\sqrt{6}$ | 0 | 547.51 | 5.1×10^{-19} | $\gamma\gamma, \pi\pi\pi$ |
| η' | $(u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$ | 0 | 957.78 | 3.2×10^{-21} | $\eta\pi\pi, \rho\gamma$ |
| D^\pm | $c\bar{d}, \bar{d}c$ | 1,-1 | 1869.3 | 1.04×10^{-12} | $K\pi\pi, K\mu\nu_\mu, K e\nu_e$ |
| D^0, \bar{D}^0 | $c\bar{u}, u\bar{c}$ | 0 | 1864.5 | 4.1×10^{-13} | $K\pi\pi, K e\nu_e, K\mu\nu_\mu$ |
| D_s^\pm | $c\bar{s}, \bar{s}c$ | 1,-1 | 1968.2 | 5.0×10^{-13} | $\eta\rho, \phi\pi\pi, \phi\rho$ |
| B^\pm | $u\bar{b}, \bar{b}u$ | 1,-1 | 5279.0 | 1.6×10^{-12} | $D^*\ell\nu_\ell, D\ell\nu_\ell, D^*\pi\pi\pi$ |
| B^0, \bar{B}^0 | $d\bar{b}, \bar{b}d$ | 0 | 5279.4 | 1.5×10^{-12} | $D^*\ell\nu_\ell, D\ell\nu_\ell, D^*\pi\pi\pi$ |

Vector Mesons (spin 1)

| Meson | Quark Content | Charge | Mass | Lifetime | Principal Decays |
|------------|--|--------|-------|---------------------|------------------------------------|
| ρ | $u\bar{d}, (u\bar{u} - d\bar{d})/\sqrt{2}, \bar{d}u$ | 1,0,-1 | 775.5 | 4×10^{-24} | $\pi\pi$ |
| K^* | $u\bar{s}, \bar{d}s, s\bar{d}, \bar{s}u$ | 1,0,-1 | 894 | 1×10^{-23} | $K\pi$ |
| ω | $(u\bar{u} + d\bar{d})/\sqrt{2}$ | 0 | 782.6 | 8×10^{-23} | $\pi\pi\pi, \pi\gamma$ |
| ψ | $c\bar{c}$ | 0 | 3097 | 7×10^{-21} | $e^+e^-, \mu^+\mu^-, 5\pi, 7\pi$ |
| D^* | $c\bar{d}, \bar{c}u, u\bar{c}, \bar{d}c$ | 1,0,-1 | 2008 | 3×10^{-21} | $D\pi, D\gamma$ |
| Υ | $b\bar{b}$ | 0 | 9460 | 1×10^{-20} | $e^+e^-, \mu^+\mu^-, \tau^+\tau^-$ |

Quarks, Léptons e Interações

| Fermions | | | | | | | | |
|----------|------|---------|----------------------------|----------------|------------|-----|-----------------------|--------|
| Quarks | | | | | Leptons | | | |
| Family | Name | q | Mass (GeV) | Forces | Name | q | Mass (GeV) | Forces |
| 1 | u | $+2/3$ | $1.5 - 3.3 \times 10^{-3}$ | S,E,W | ν_e | 0 | ≈ 0 | W |
| 1 | d | $-1/3$ | $3.5 - 6.0 \times 10^{-3}$ | S,E,W | e | -1 | 5.11×10^{-4} | E,W |
| 2 | c | $+2/3$ | 1.27 | S,E,W | ν_μ | 0 | ≈ 0 | W |
| 2 | s | $-1/3$ | 0.104 | S,E,W | μ | -1 | 0.105 | E,W |
| 3 | t | $+2/3$ | 171.2 | S,E,W | ν_τ | 0 | ≈ 0 | W |
| 3 | b | $-1/3$ | 4.2 | S,E,W | τ | -1 | 1.77 | E,W |
| Bosons | | | | | | | | |
| Name | | q | Mass (GeV) | Force Mediated | | | | |
| g | | 0 | 0 | S | | | | |
| γ | | 0 | 0 | E | | | | |
| W^\pm | | ± 1 | 80.4 | W | | | | |
| Z | | 0 | 91.2 | W | | | | |

Quarks, Léptons e Interações

| Fermions | | | | | | | | |
|----------|----------|---------|----------------------------|----------------|------------|-----|-----------------------|--------|
| Quarks | | | | | Leptons | | | |
| Family | Name | q | Mass (GeV) | Forces | Name | q | Mass (GeV) | Forces |
| 1 | u | $+2/3$ | $1.5 - 3.3 \times 10^{-3}$ | S,E,W | ν_e | 0 | ≈ 0 | W |
| 1 | d | $-1/3$ | $3.5 - 6.0 \times 10^{-3}$ | S,E,W | e | -1 | 5.11×10^{-4} | E,W |
| 2 | c | $+2/3$ | 1.27 | S,E,W | ν_μ | 0 | ≈ 0 | W |
| 2 | s | $-1/3$ | 0.104 | S,E,W | μ | -1 | 0.105 | E,W |
| 3 | t | $+2/3$ | 171.2 | S,E,W | ν_τ | 0 | ≈ 0 | W |
| 3 | b | $-1/3$ | 4.2 | S,E,W | τ | -1 | 1.77 | E,W |
| Bosons | | | | | | | | |
| | Name | q | Mass (GeV) | Force Mediated | | | | |
| | g | 0 | 0 | S | | | | |
| | γ | 0 | 0 | E | | | | |
| | W^\pm | ± 1 | 80.4 | W | | | | |
| | Z | 0 | 91.2 | W | | | | |

Medidos em 1983
(previstos em 1967)²⁵

Medida dos Bósons W e Z

- Carlo Rubbia e Simon van der Meer

previsão: $M_W > 37 \text{ GeV}/c^2$ e $M_Z > 75 \text{ GeV}/c^2$ (1967)

$M_W = 82 \pm 2 \text{ GeV}/c^2$ e $M_Z = 92 \pm 2 \text{ GeV}/c^2$ (1982)

medido: $M_W = 80.403 \pm 0.029 \text{ GeV}$

e $M_Z = 91.1888 \pm 0.002 \text{ GeV}$ (1983)



Nobel
Prize

1984

Teoria Eletrofraca

- Glashow-Weinberg-Salam

previsão: $M_W > 37 \text{ GeV}/c^2$ e $M_Z > 75 \text{ GeV}/c^2$ (1967)

$M_W = 82 \pm 2 \text{ GeV}/c^2$ e $M_Z = 92 \pm 2 \text{ GeV}/c^2$ (1982)

medido: $M_W = 80.403 \pm 0.029 \text{ GeV}$

e $M_Z = 91.1888 \pm 0.002 \text{ GeV}$ (1983)



Nobel
Prize

1979

27

Teoria Eletrofraca

- Glashow-Weinberg-Salam

O modelo começa com simetria local $SU(2) \times U(1)$, com campos de gauge (W^+ , W^- , W^0) e B^0 , todos sem massa, e bóson de Higgs. Quebra espontânea de simetria conduz aos massivos W^\pm e Z^0 e ao usual fóton sem massa via [mecanismo de Higgs](#).



Nobel
Prize

1979

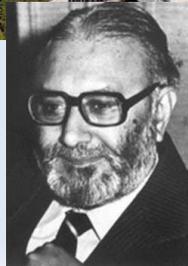
28

The Abdus Salam ICTP

- International Center for Theoretical Physics



Trieste - Itália



Nobel
Prize
1979

29

The Abdus Salam ICTP

- International Center for Theoretical Physics
- ICTP South American Institute for Fundamental Research – São Paulo, Brazil (IFT) 2012



Nobel
Prize
1979

30

Sabor de Teoria de Campos

Invariância de Gauge

$$\mathcal{L} = \bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi$$

simetria global

$$\psi(x) \rightarrow \exp(i\theta)\psi(x) \text{ transformação de fase global}$$

generalização

$$\psi(x) \rightarrow \exp(i\theta(x))\psi(x) \text{ transformação de fase local}$$

$$\partial_\mu(\exp(i\theta)\psi) = i\partial_\mu\theta \exp(i\theta)\psi + \exp(i\theta)\partial_\mu\psi$$

introdução de campo de gauge A_μ

$$D_\mu \equiv \partial_\mu + ieA_\mu$$

$$A_\mu \rightarrow A_\mu - \frac{1}{e}\partial_\mu\theta$$

$$\mathcal{L} = \bar{\psi}\gamma^\mu D_\mu\psi - m\bar{\psi}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + m_A^2 A_\mu A^\mu$$

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31

Sabor de Teoria de Campos

Invariância de Gauge

$$\mathcal{L} = \bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi$$

simetria global

$$\psi(x) \rightarrow \exp(i\theta)\psi(x) \text{ transformação de fase global}$$

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$$\psi(x) \rightarrow \exp(i\theta(x))\psi(x) \text{ transformação de fase local}$$

$$\partial_\mu(\exp(i\theta)\psi) = i\partial_\mu\theta \exp(i\theta)\psi + \exp(i\theta)\partial_\mu\psi$$

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$$A_\mu \rightarrow A_\mu - \frac{1}{e}\partial_\mu\theta$$

$$\mathcal{L} = \bar{\psi}\gamma^\mu D_\mu\psi - m\bar{\psi}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + m_A^2 A_\mu A^\mu$$

32

Sabor de Teoria de Campos

Transformação mais geral:

$$\psi(x) \rightarrow U\psi(x), \quad U \in G$$

Lagrangiana para cromodinâmica:

$$\mathcal{L} = [\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi] - \frac{1}{4}\mathbf{F}_{\mu\nu}\mathbf{F}^{\mu\nu} - e\bar{\psi}\gamma^\mu\mathbf{T}\psi \cdot \mathbf{A}_\mu$$

\mathbf{T} → geradores do grupo SU(3) (matrizes de Gell-Mann)

Quebra Espontânea de Simetria

$$\mathcal{L} = \frac{1}{2}(\partial_\mu\phi)(\partial^\mu\phi) + \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}\lambda^2\phi^4$$

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

mínimo: $\phi = \pm\mu/\lambda$

$$\eta = \phi \pm \mu/\lambda$$

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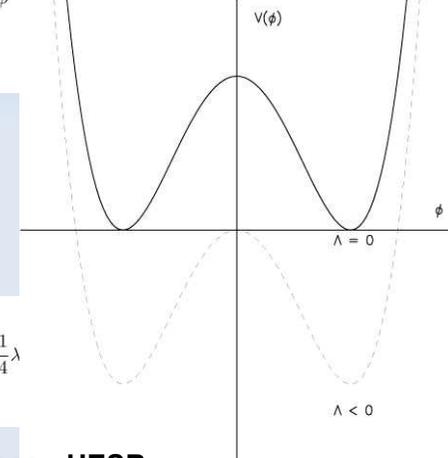
simetria original

$$\phi \rightarrow -\phi$$

nova lagrangiana

$$\mathcal{L} = \frac{1}{2}(\partial_\mu\eta)(\partial^\mu\eta) - \mu^2\eta^2 \pm \mu\lambda\eta^3 - \frac{1}{4}\lambda$$

massa gerada $m = \sqrt{2}\mu$



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O Mecanismo de Higgs

$\phi \equiv \phi_1 + i\phi_2$ (par de campos reais)

$\phi^* \phi = \phi_1^2 + \phi_2^2$ (campo complexo)

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^*(\partial^\mu \phi) + \frac{1}{2}\mu^2(\phi^* \phi) - \frac{1}{4}\lambda^2(\phi^* \phi)^2$$

$\phi \rightarrow e^{i\theta} \phi$ simetria global

$\phi \rightarrow e^{i\theta(x)} \phi$ simetria local

$D_\mu \equiv \partial_\mu + iqA_\mu$ derivada covariante - acoplamento mínimo

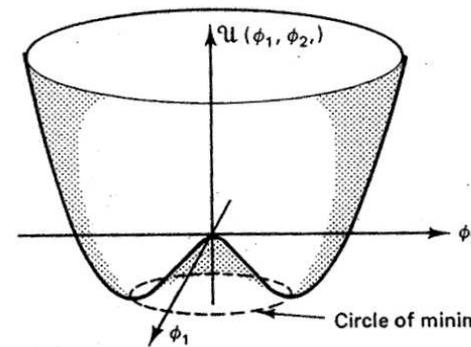
$$\mathcal{L} = \frac{1}{2} [D_\mu \phi^*] [D^\mu \phi] + \frac{1}{2}\mu^2(\phi^* \phi) - \frac{1}{4}\lambda^2(\phi^* \phi)^2 - \frac{1}{4}F^{\mu\nu} F_{\mu\nu}$$

$$\eta \equiv \phi_1 - \mu/\lambda, \quad \xi \equiv \phi_2$$

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35

O Mecanismo de Higgs



campos reais)

o complexo)

$$(\partial_\mu \phi)^*(\partial^\mu \phi) - \frac{1}{4}\lambda^2(\phi^* \phi)^2$$

a global

ria local

ie - acoplamento mínimo

$$\mathcal{L} = \frac{1}{2} [D_\mu \phi^*] [D^\mu \phi] + \frac{1}{2}\mu^2(\phi^* \phi) - \frac{1}{4}\lambda^2(\phi^* \phi)^2 - \frac{1}{4}F^{\mu\nu} F_{\mu\nu}$$

$$\eta \equiv \phi_1 - \mu/\lambda, \quad \xi \equiv \phi_2$$

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36

O Mecanismo de Higgs

$$\begin{aligned}
 \mathcal{L} = & \left[\frac{1}{2}(\partial_\mu \eta)(\partial^\mu \eta) - \mu^2 \eta^2 \right] + \left[\frac{1}{2}(\partial_\mu \xi)(\partial^\mu \xi) \right] \\
 & + \left[-\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}\left(q\frac{\mu}{\lambda}\right)^2(A_\mu A^\mu) \right] \\
 & + q[\eta(\partial_\mu \xi) - \xi(\partial_\mu \eta)]A^\mu + \frac{\mu}{\lambda}q^2\eta(A_\mu A^\mu) \\
 & + \frac{1}{2}q^2(\xi^2 + \eta^2)(A_\mu A^\mu) - \lambda\mu(\eta^3 + \eta\xi^2) - \frac{1}{4}\lambda^2(\eta^4 + 2\eta^2\xi^2 + \xi^4) \\
 & + \frac{\mu}{\lambda}(\partial_\mu \xi)A^\mu + \frac{\mu^2}{2\lambda}
 \end{aligned}$$

$$m_A = 2q\frac{\mu}{\lambda}, \text{ massa para o campo de gauge}$$

O Mecanismo de Higgs

$$\begin{aligned}
 \mathcal{L} = & \left[\frac{1}{2}(\partial_\mu \eta)(\partial^\mu \eta) - \mu^2 \eta^2 \right] + \left[\frac{1}{2}(\partial_\mu \xi)(\partial^\mu \xi) \right] \\
 & + \left[-\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}\left(q\frac{\mu}{\lambda}\right)^2(A_\mu A^\mu) \right] \\
 & + q[\eta(\partial_\mu \xi) - \xi(\partial_\mu \eta)]A^\mu + \frac{\mu}{\lambda}q^2\eta(A_\mu A^\mu) \\
 & + \frac{1}{2}q^2(\xi^2 + \eta^2)(A_\mu A^\mu) - \lambda\mu(\eta^3 + \eta\xi^2) - \frac{1}{4}\lambda^2(\eta^4 + 2\eta^2\xi^2 + \xi^4) \\
 & + \frac{\mu}{\lambda}(\partial_\mu \xi)A^\mu + \frac{\mu^2}{2\lambda}
 \end{aligned}$$

$$m_A = 2q\frac{\mu}{\lambda}, \text{ massa para o campo de gauge}$$

Peter Higgs

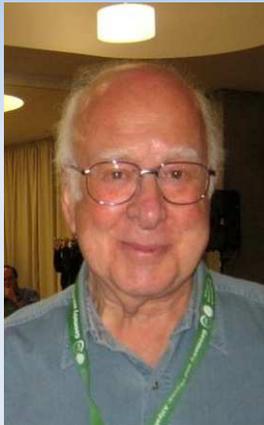
Peter Ware Higgs
(Newcastle – England, 1929)

Tese de Doutorado: Some problems in the theory of molecular vibrations (1955)

P.W. Higgs, Phys. Lett. 12 (1964) 132

P.W. Higgs, Phys. Rev. Lett. 13 (1964) 508

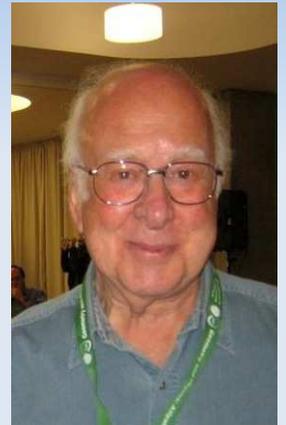
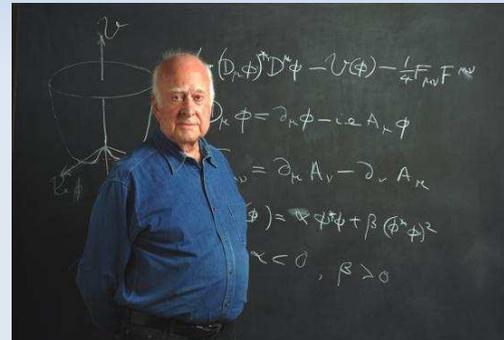
Aluno de doutorado: Lewis Ryder



39

Peter Higgs

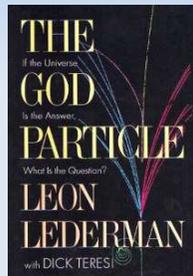
Peter Ware Higgs
(Newcastle – England, 1929)



40

Partícula de Deus

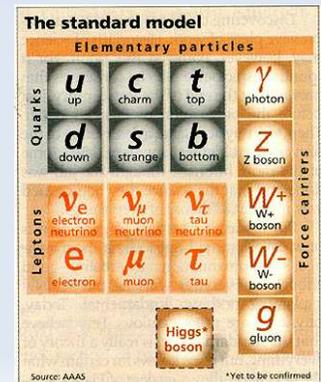
- Leon Lederman (1922, New York)
- Prêmio Nobel em 1988
- The God Particle (1993)
- Diretor Emérito do Fermilab



41

Críticas ao Modelo Padrão

- Não permite *calcular* as massas de quarks e léptons.
 - Total de 20 parâmetros arbitrários (massas, ângulos e fases internas)
 - Não inclui a gravitação
 - Se baseia no ainda não observado bóson de Higgs
- ~~114 GeV < m < 250 GeV~~



Large Hadron Collider (LHC)



7 experimentos: ALICE, ATLAS, CMS, TOTEM, LHCb, LHCf e MoEDAL

Organisation Européenne pour la Recherche Nucléaire

43



4 de julho de 2012

- Detectado no LHC, CERN um bóson Higgslike de massa **125 a 127 GeV/c²**



Dentro da faixa esperada: $114 \text{ GeV} < m < 250 \text{ GeV}$

45

4 de julho de 2012

- Detectado no LHC, CERN um bóson Higgslike de massa **125 a 127 GeV/c²**



Fabiola Gianotti e Higgs

Higgs: "It's really an incredible thing that it's happened in my lifetime."

Problemas em Aberto

- Ajuste do Modelo Padrão
- Confinamento de Quarks e Glúons
- Quantização da Gravitação
- Matéria Escura (Dark Matter)
- Assimetria Matéria/Antimatéria

47

Novo Referencial Teórico?

- Great Unifying Theories (GUT's) – Teoria de Tudo
- Supersimetria (SUSY)
- Teoria de Cordas
- Teoria Quântica de Campos Axiomática

48

Leituras Recomendadas

- Livros de Divulgação
 - Sonhos de Uma Teoria Final (Weinberg – 1994)
 - The God Particle: If the Universe Is the Answer, What Is the Question? (Lederman e Teresi – 1993)
 - A Estrutura das Revoluções Científicas (Kuhn – 1962)
 - The Quark and The Jaguar (Gell-Mann – 1995)

49

Leituras Recomendadas

- Textos Técnicos
 - Introduction to Elementary Particles (Griffiths, 2008)
 - Standard Model: An Introduction (Novaes, 2000)
 - Quantum Field Theory (Ryder, 1996)

50