

# Interações Fortes

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COHEP/CBPF

## Sumário

I - Questões Fundamentais

II - Partículas Elementares

III - Evolução das Interações e o Modelo Padrão

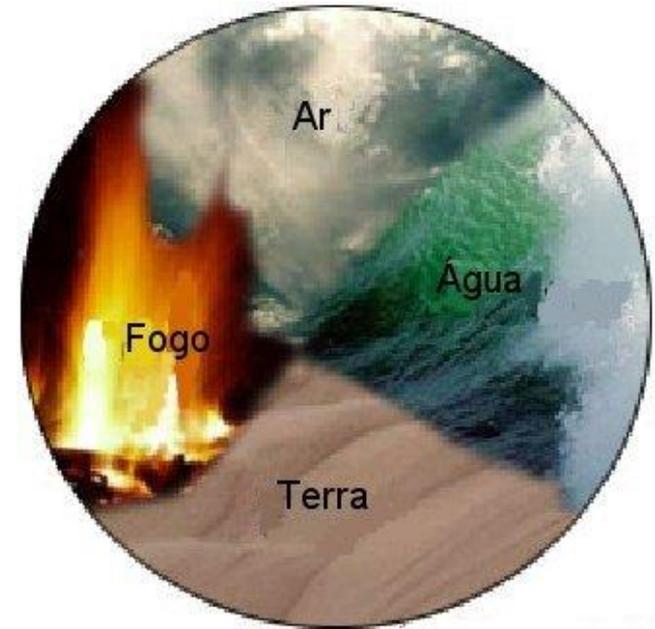
# A Questão Milenar



Do que o mundo é feito??



**Leucipo (Demócrito – 400AC)  
Átomos e Vazio**

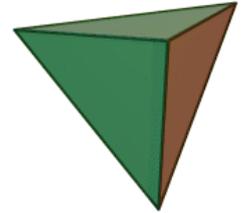


**Empédocles (450 AC)  
4 Elementos e Éter**

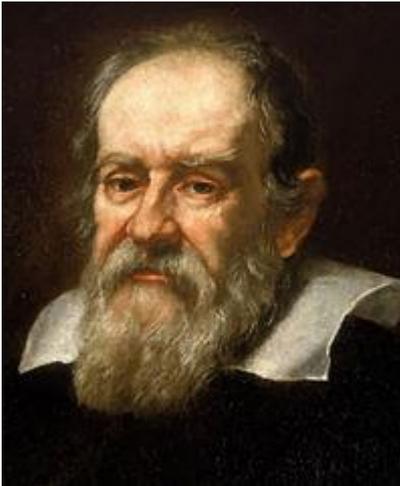
# Platão e Aristóteles (350 BC)



- Rejeitam o atomismo
  - Vazio não natural
- Adotam o pluralismo
  - Elementos  $\leftrightarrow$  Sólidos regulares
- Domina o pensamento até o fim da idade média

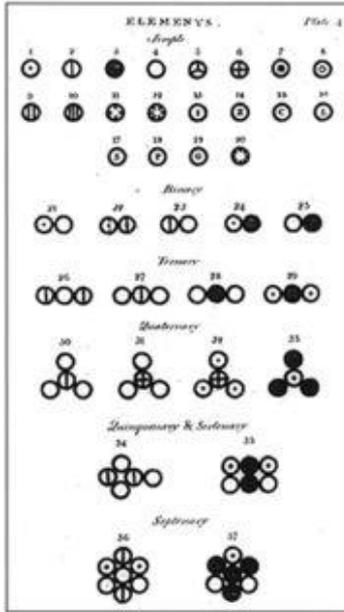


# Galileu Galilei (1600)



- Método científico
  - Experimentos quantitativos
  - Análise matemática
  - Contesta Aristóteles
  - Atomismo (parcialmente)

# John Dalton (1808)



- Estabelece as Bases da Teoria Atômica Moderna
  - Síntese dos Experimentos
  - Lavoisier
    - Conservação das Massas
  - Proust
    - Lei das proporções definidas
- Os elementos são constituídos de átomos
- Os átomos não podem ser criados ou destruídos
- Átomos de diversos elementos podem se combinar em substâncias compostas

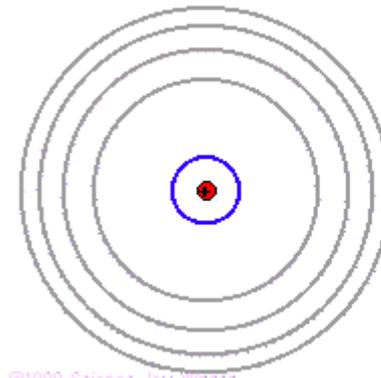
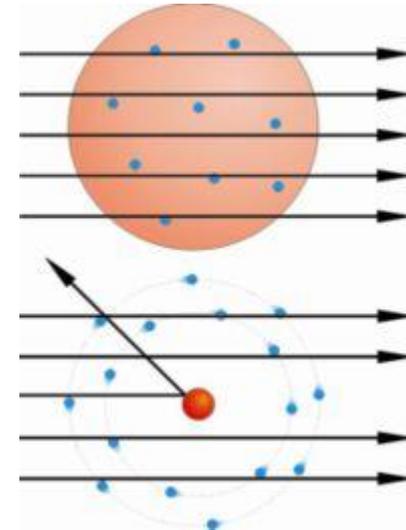
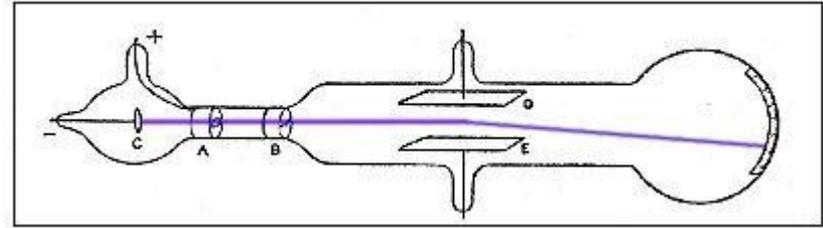
# Dmitri Mendeleev (1869)

- Criou a 1ª Tabela Periódica
- Previu a existência de novos elementos

Period	Group										(0)
	I a	II b	III a	IV b	V a	VI b	VII a	VIII b			
1	H 1.0										He 4.0
2	Li 6.9	Be 9.0	B 10.8	C 12.0	N 14.0	O 16.0	F 19.0				Ne 20.2
3	Na 23.0	Mg 24.3	Al 27.0	Si 28.1	P 31.0	S 32.1	Cl 35.5				Ar 39.9
4	K 39.1	Ca 40.1	Sc 45.0	Ti 47.9	V 50.9	Cr 52.0	Mn 54.9	Fe 55.8	Co 58.9	Ni 58.7	
		Cu 63.5	Zn 65.4	Ga 69.7	Ge 72.6	As 74.9	Se 79.0	Br 79.9			Kr 83.8
5	Rb 85.5	Sr 87.6	Y 88.9	Zr 91.2	Nb 92.9	Mo 95.9	Tc	Ru 101.1	Rh 102.9	Pd 106.4	
		Ag 107.9	Cd 112.4	In 114.8	Sn 118.7	Sb 121.8	Te 127.6	I 126.9			Xe 131.3
6	Cs 132.9	Ba 137.3	La* 138.9	Hf 178.5	Ta 180.9	W 183.9	Re 186.2	Os 190.2	Ir 192.2	Pt 195.1	
		Au 197.0	Hg 200.6	Tl 204.4	Pb 207.2	Bi 209.0	Po	At			Rn
7	Fr	Ra	Ac**								

* Ce 140.1	Pr 140.9	Nd 144.2	Pm	Sm 150.4	Eu 152.0	Gd 157.3	Tb 158.9	Dy 162.5	Ho 164.9	Er 167.3	Tm 168.9	Yb 173.0	Lu 175.0
* Th 232.0	Pa	U 238.0	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

- Problemas, problemas...
  - Centenas de “Átomos”
  - Estados excitados
- J.J.Thompson (1897)
  - **Início da Física de Partículas**
    - Descoberta do elétron
  - Modelo de Thompson
- Ernest Rutherford (1911)
  - Modelo nuclear
  - Mais problemas
    - irradiação
- Niels Bohr (1913)
  - Modelo pré-quântico



$n=\infty$	0.00eV
$n=5$	-0.54eV
$n=4$	-0.85eV
$n=3$	-1.51eV
$n=2$	-3.40eV
$n=1$	-13.6eV

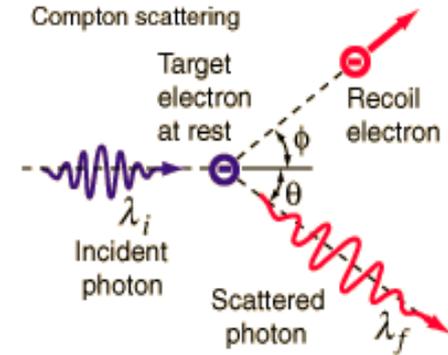
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Rutherford (1918) e Chadwick (1932)

- prótons e nêutrons

Partículas Elementares – novos átomos

- $p$ ,  $n$ ,  $e^-$ ,  $\gamma \rightarrow$  espalhamento Compton
- **breve simplicidade**
- Anderson (1932) – pósitron ( $e^+$ )  $\rightarrow$  Dirac

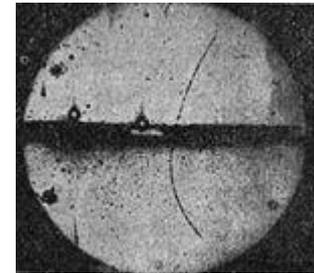


- Problemas (de novo) – Estabilidade nuclear

- Radioatividade (Fermi 1933) e Repulsão Coulombiana

- Magnitude das Interações Fundamentais

- EM x Gravitacional
- $k e^2/R$  x  $G m^2/R$
- $1$  x  $10^{-38}$  !!

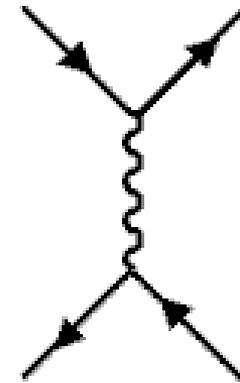


- Nova força (interação forte)

- Curto alcance – restrita a escala nuclear

- O que determina o alcance de uma força???

- Honestamente ???
- TQC – Interação  $\leftarrow \rightarrow$  troca de “mensageiro”
- Massa do mensageiro  $\rightarrow$  alcance



- 1926 Klein-Gordon (relatividade → TQC)

$$-\frac{1}{c^2} \frac{\partial^2 V}{\partial t^2} + \nabla^2 V = \frac{m^2 c^2}{\hbar^2} V$$

- 1933 Solvay Conf.

– Heisenberg → Troca de  $e^-$

- Problemas... Spin, potencial...
- Fermi → Decaimento  $\beta$  (int. fraca)

– Yukawa (1935)

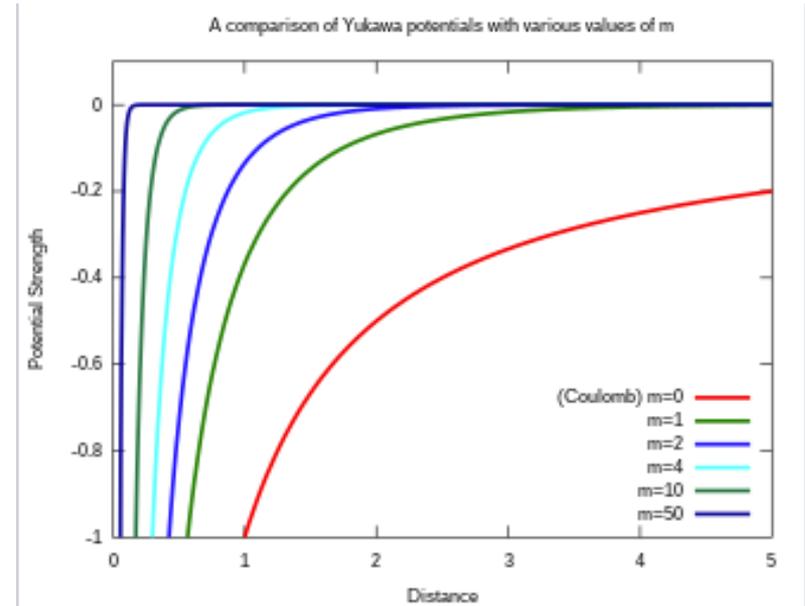
- Solução Eq. K-G

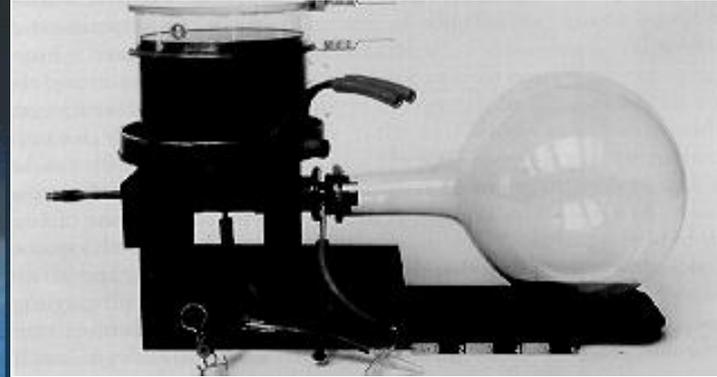
$$V_{\text{Yukawa}}(r) = -g^2 \frac{e^{-\alpha mr}}{r}$$

- $m=0 \rightarrow$  Coulomb

$$- \Delta E \Delta t = mc^2 \Delta R v^{-1} \sim \hbar$$

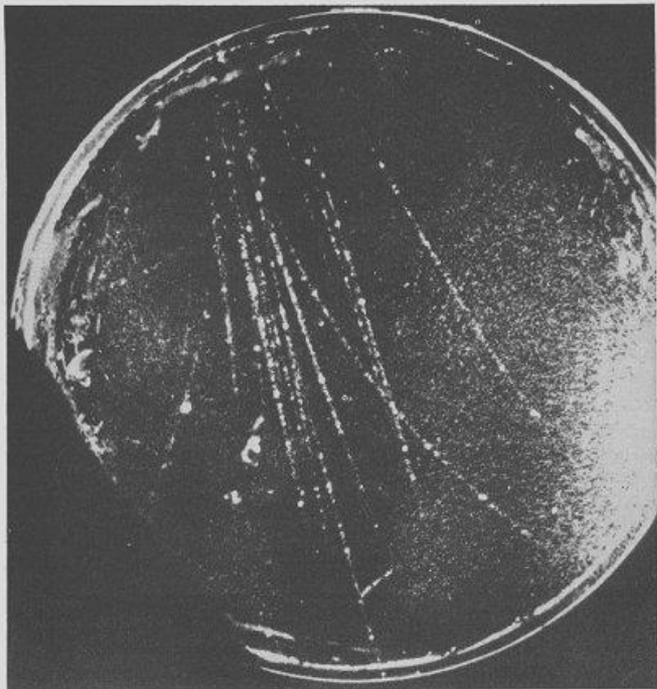
- $\Delta R \approx 10^{-15} \text{m} \rightarrow m \approx 200 m_e$



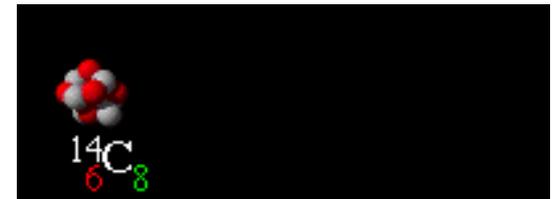
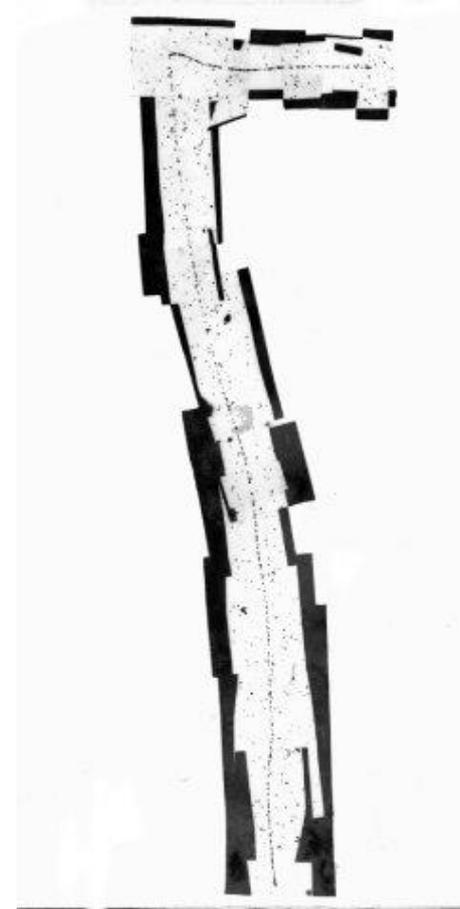


## 1937 – 1947 procura pelo méson de Yukawa em Raios Cósmiticos

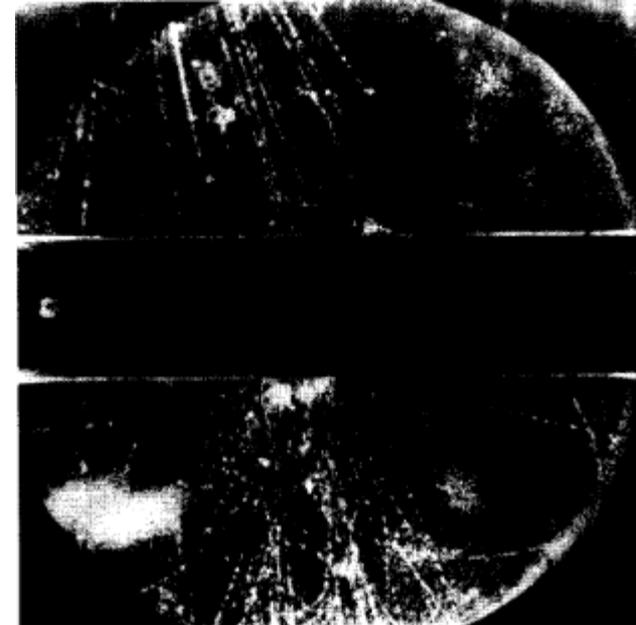
- A grande “pegadinha” da natureza
- 1937 – Anderson → “méson”  $\sim 200 m_e$   
– raios cósmiticos
- 1945 – Conversi, Pancini & Piccioni –  
Interação fraca  $\tau \approx 10^{-6} s !!$
- 1946 – Perkins – dois tipos de mésons



- 1947 - Lattes, Occhialini & Powell  
decaimento  $\pi \rightarrow \mu$
- $\mu$  (Anderson) == elétron pesado
- “Who ordered that??” I.I.Rabi
  
- Falta alguma coisa...
  - $\pi \rightarrow \mu + ?$
  
- W. Pauli (1930) Decaimento beta
  - partícula neutra (neutrino -  $\nu$ )
- Seria a mesma partícula??
  
- Frederick Reines & Clyde Cowan (1956)
  - 1ª observação direta  $\nu + \bar{p} \rightarrow n + e^+$
- Leon Lederman (1962)
  - $\nu_\mu \neq \nu_e$

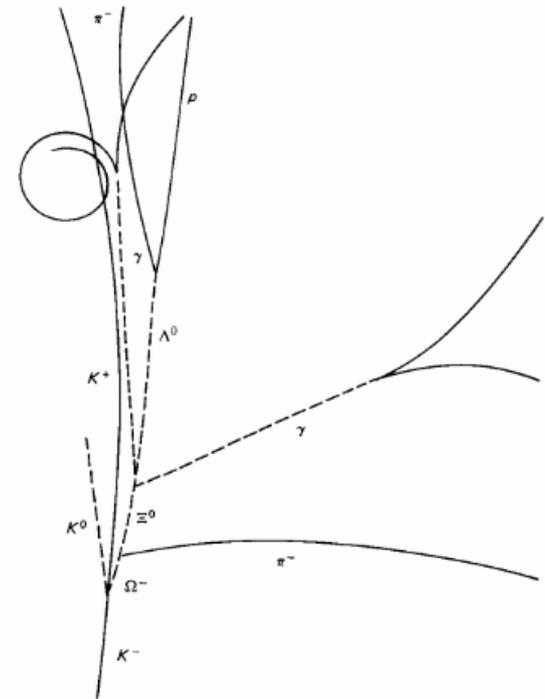
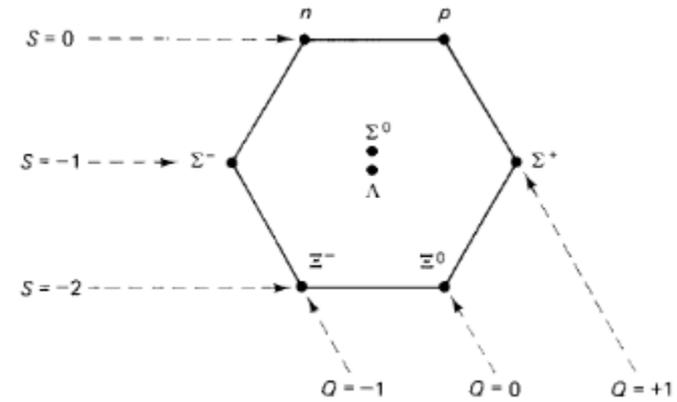


- (1947-1950) Partículas estranhas (mesmo)
  - Produzidas em pares
  - Vida média extremamente elevada
    - $K^0 \rightarrow \pi^+ + \pi^-$  ( $\tau \approx 10^{-10}$  s)
    - $\rho^0 \rightarrow \pi^+ + \pi^-$  ( $\tau \approx 10^{-23}$  s)
  - Uma família de partículas estranhas
    - $K^0, K^+, K^-, \Lambda, \Sigma^+, \Xi^+, \Sigma^-, \Xi^-, \dots$



- Abraham Pais & Murray Gell-Mann (1953)  $\rightarrow$  novo número quântico – s
  - Conservado pela Interação forte
    - Produção em pares
  - Partículas estranhas decaem via Interação fraca (decaimento beta)
    - Vida média

- (1960) Física de Partículas está uma enorme confusão
  - Centenas de partículas
    - bárions, mésons, léptons, ...
  - Nenhuma ordem aparente
- Murray Gell-Mann & Yuval Ne'eman (1961)
  - regra do octeto (simetria SU(3))
  - classificação das partículas – Q, S, J
  - nova tabela periódica
  - prevê a existência de novas partículas ( $\Omega^-$ )



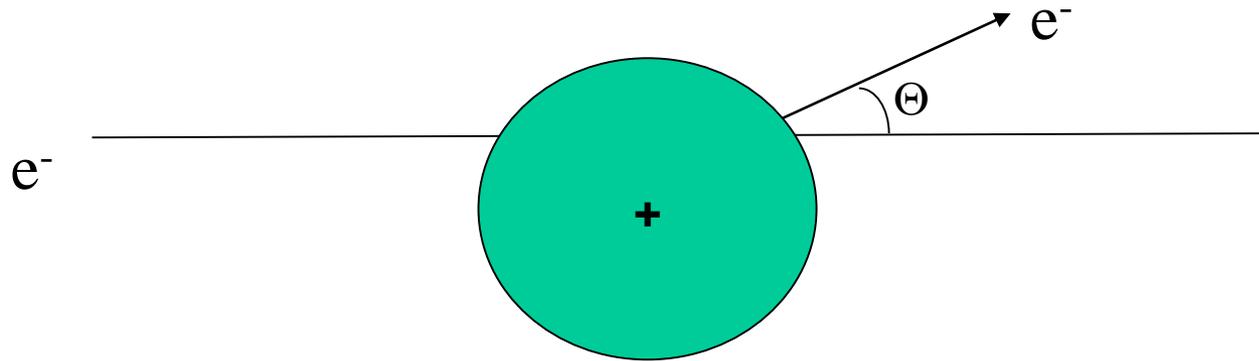
- O sucesso da regra do octeto levanta novamente a questão
  - São essas partículas elementares?
  - “Young man, if I could remember the names of these particles, I would have been a botanist” E. Fermi
- Kazuhiko Nishijima, Murray Gell-Mann & George Zweig (1964)
  - Hádrõs compostos por férmions (spin  $\frac{1}{2}$ ) fundamentais (quarks)
    - “Three quarks for Muster Mark” – Finnegans Wake (James Joyce)
  - Bárions  $\rightarrow$  três quarks
  - Mésons  $\rightarrow$  quark-antiquark

$qqq$	$Q$	$S$	Baryon
$uuu$	2	0	$\Delta^{++}$
$uud$	1	0	$\Delta^+$
$udd$	0	0	$\Delta^0$
$ddd$	-1	0	$\Delta^-$
$uus$	1	-1	$\Sigma^{*+}$
$uds$	0	-1	$\Sigma^{*0}$
$dds$	-1	-1	$\Sigma^{*-}$
$uss$	0	-2	$\Xi^{*0}$
$dss$	-1	-2	$\Xi^{*-}$
$sss$	-1	-3	$\Omega^-$

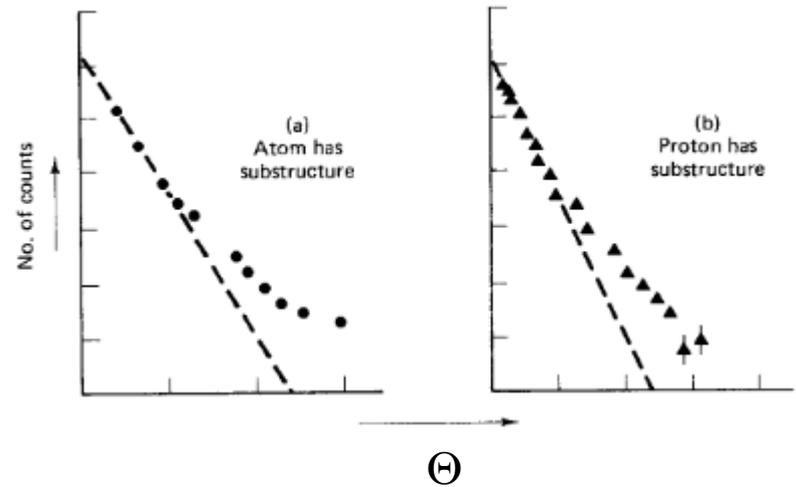
$q\bar{q}$	$Q$	$S$	Meson
$u\bar{u}$	0	0	$\pi^0$
$u\bar{d}$	1	0	$\pi^+$
$d\bar{u}$	-1	0	$\pi^-$
$d\bar{d}$	0	0	$\eta$
$u\bar{s}$	1	1	$K^+$
$d\bar{s}$	0	1	$K^0$
$s\bar{u}$	-1	-1	$K^-$
$s\bar{d}$	0	-1	$\bar{K}^0$
$s\bar{s}$	0	0	??



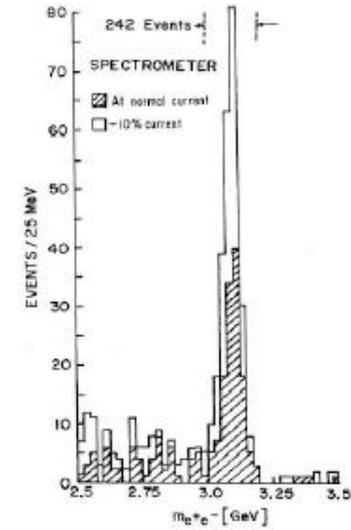
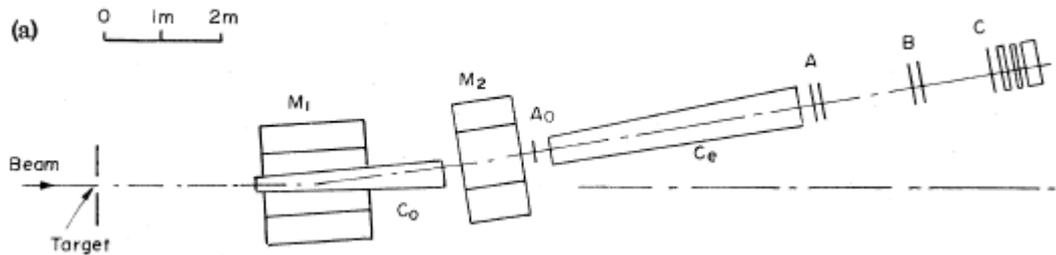
- Mais Problemas (não tem fim)
  - Não se observam quarks livres
  - quarks tem carga fracionária
  - Violam o princípio de Pauli??
    - $\Omega^- (s\uparrow s\uparrow s\uparrow)$   $\Delta^- (d\uparrow d\uparrow d\uparrow)$ ,  $\Delta^{++} (u\uparrow u\uparrow u\uparrow)$
- Até hoje não foram observados quarks livres ou carga fracionária
- Oscar Greenberg (1964)
  - quarks tem um novo n° quântico (cor)
  - três cores fundamentais (**R**, **G**, **B**)
  - partículas observáveis não tem cor  $\Rightarrow$  confinamento
  - $\Omega^- (s\uparrow s\uparrow s\uparrow)$
  - Socorro!!



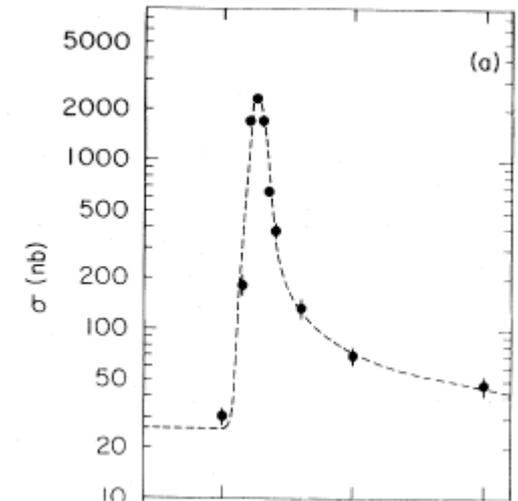
- (1969) espalhamento  $e^-p$  a altas energias  $\rightarrow$  Rutherford
  - partons = quarks??



- (1974) Descoberta de uma partícula com propriedades incomuns
  - Revolução de Novembro
- Samuel Ting (Brookhaven)  $pp \rightarrow e^+e^-$



- Burton Richards (SLAC)  $e^+e^- \rightarrow pp$



- propriedades incomuns
  - Massa elevada  $\approx 3.1 \text{ GeV}$  (próton  $\approx 1 \text{ GeV}$ )
  - Vida média elevada ( $\approx 1000x$ )
    - Semelhante as partículas estranhas
- Novo número quântico – c (charme)
- Proposto por Glashow, Iliopoulos & Maiani (1970)
  - simetria quarks  $\Leftrightarrow$  léptons

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} s \end{pmatrix} \quad \begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$$

- Anomalias no decaimento  $K^0 \rightarrow \mu^+\mu^-$

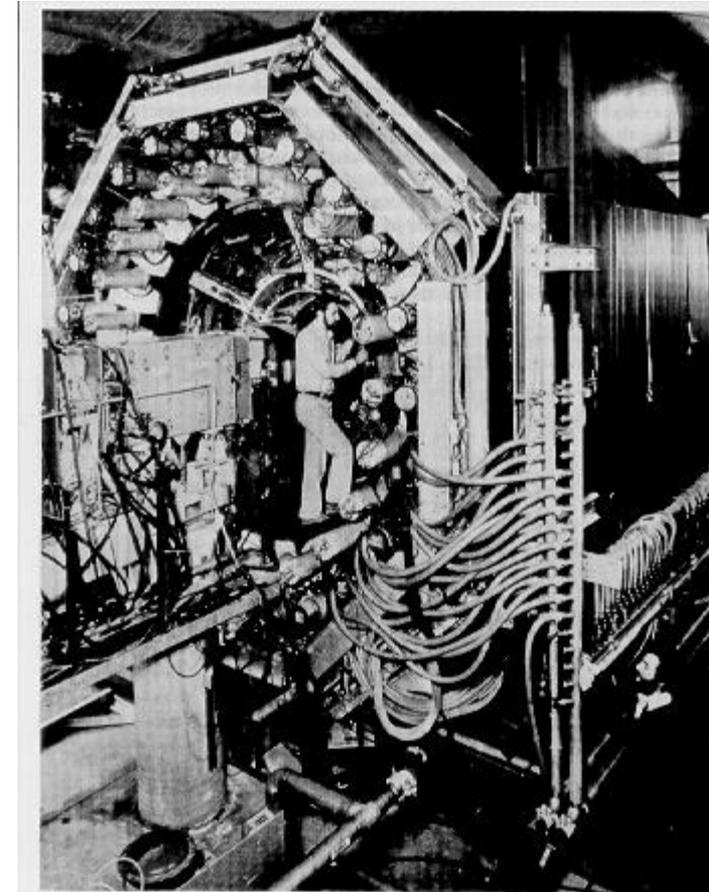
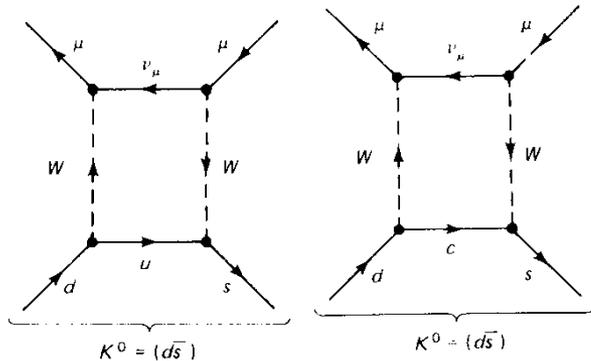


Photo 9B Detecting the results of electron-positron annihilation at SPEAR. After the electron and positron have annihilated, new matter and antimatter can be created. This is detected by the array of electronic devices shown. Electrons enter at one end and positrons at the other end, the annihilation occurring in the tunnel behind Roy Schwitters. In this way the  $J/\psi$  and charmed particles were discovered. (Courtesy SLAC)

- O maior problema foi achar um nome...

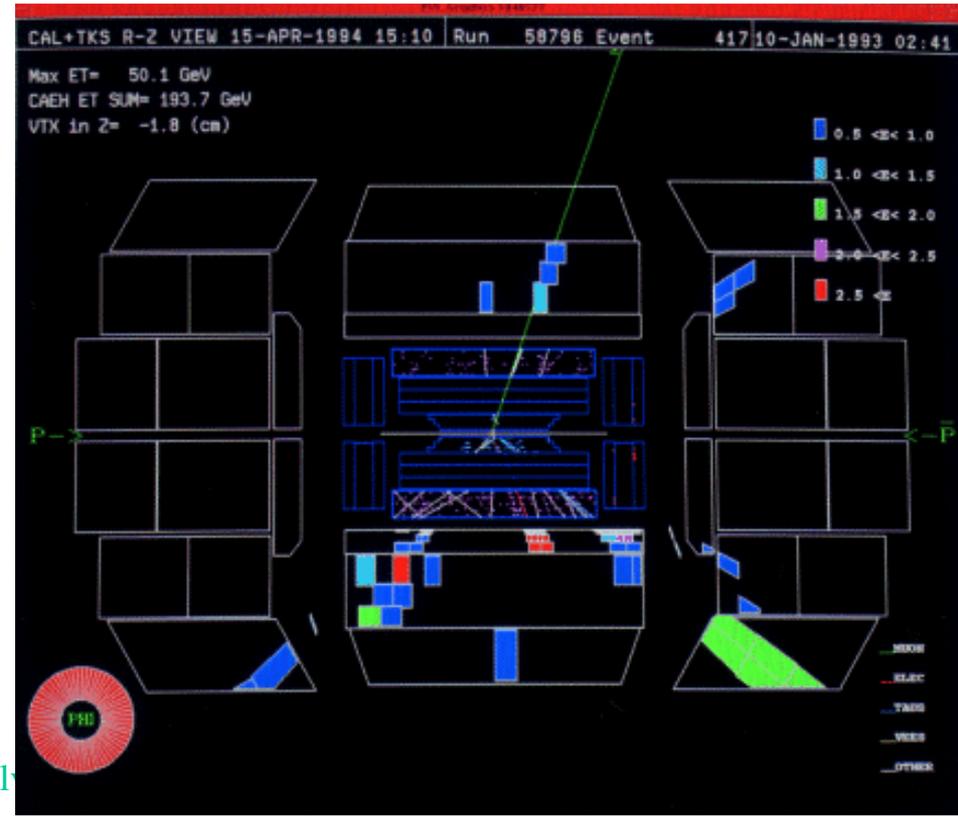
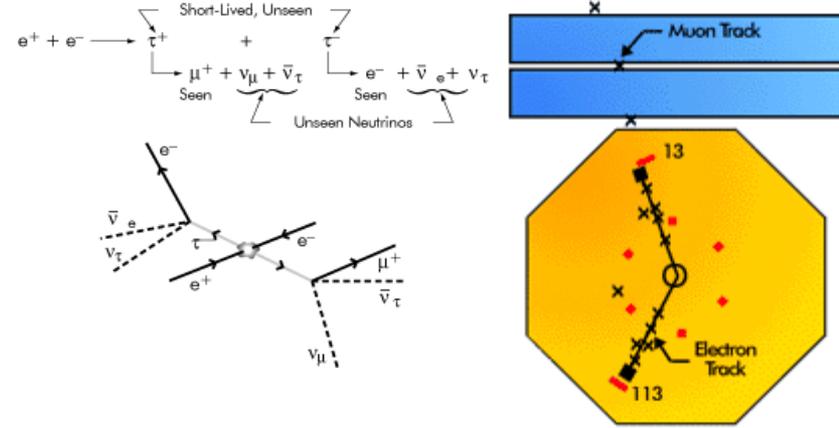
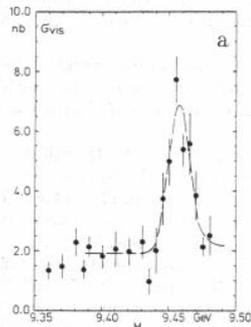
- Ting – méson J
- Richter – méson  $\psi$
- no fim – méson J/ $\psi$

- Novas partículas contendo charme (1975)
- Mas antes outra “pegadinha”

- Descoberta do lépton  $\tau$  (1975)

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} ? \\ ? \end{pmatrix} \quad \begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

- 1977 – Lederman et al.  $\rightarrow \Upsilon$
- 1995 – DØ & CDF  $\rightarrow$  top quark



# Modelo Padrão

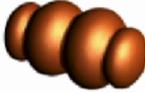
- 6 quarks e léptons (+ antipartículas)
- 4 interações (mediadores -  $\gamma$ , g, W/Z, graviton?)
- Todas partículas fundamentais (sem estrutura)

### Leptons

Tau		-1	0		Tau Neutrino
Muon		-1	0		Muon Neutrino
Electron		-1	0		Electron Neutrino

Electric Charge

### Strong

Gluons (8) 

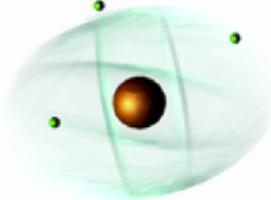
Quarks 

Mesons  Baryons 

Nuclei 

### Electromagnetic

Photon 

Atoms 

Light  
Chemistry  
Electronics

### Quarks

Bottom		-1/3	2/3		Top
Strange		-1/3	2/3		Charm
Down		-1/3	2/3		Up

each quark: R, B, G 3 colors

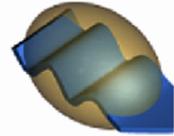
### Gravitational

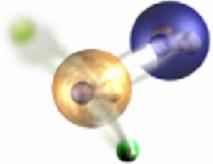
Graviton ? 

Solar system 

Galaxies  
Black holes

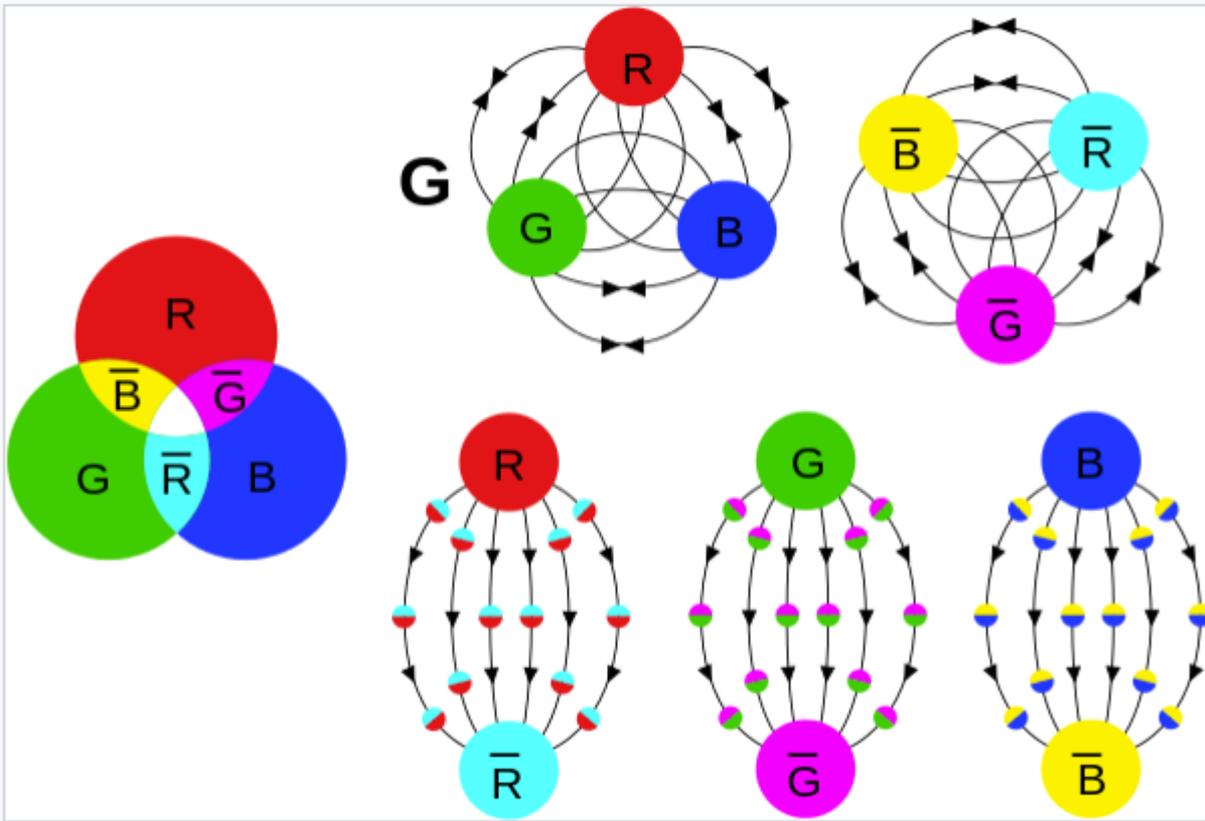
### Weak

Bosons (W,Z) 

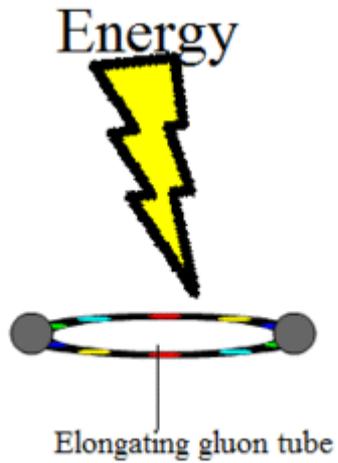
Neutron decay  
Beta radioactivity  
Neutrino interactions  
Burning of the sun 

# O que é a essa “Cor” dos Quarks?

- Não se observam quarks livres
- Hipótese do confinamento de cor
  - partículas observáveis não tem cor  $\rightarrow$  analogia óptica



- Hipótese do confinamento de cor  $\rightarrow F = -kx$ 
  - Solução Analítica ?? Lattice QCD



# O que é a essa “Cor” dos Quarks?

- Evidências de cor?
- Razão R →

$$R \equiv \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

$$= 3 \sum_{\text{flavour}} e_{qi}^2$$

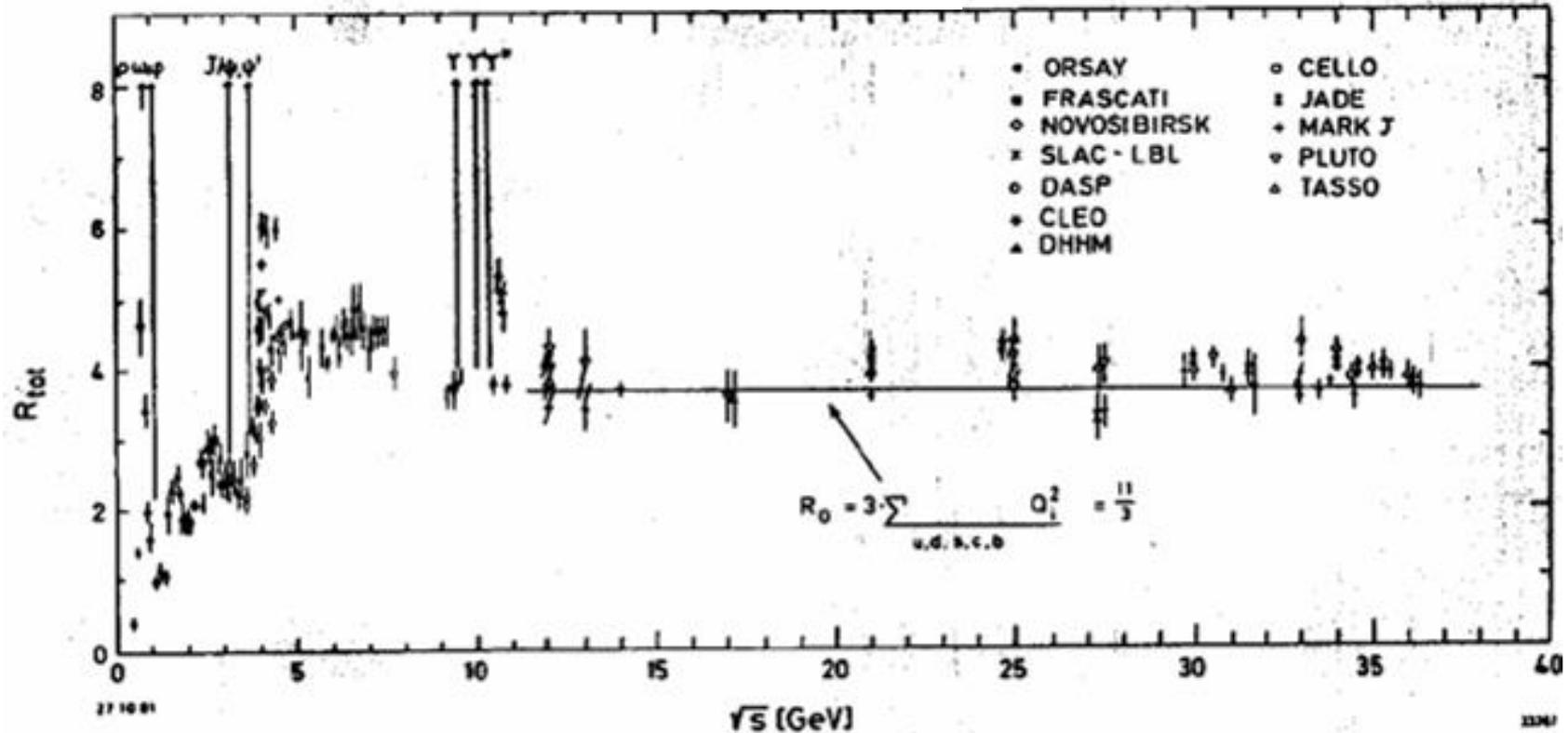
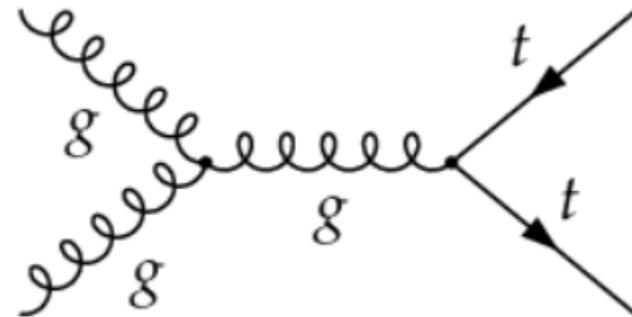
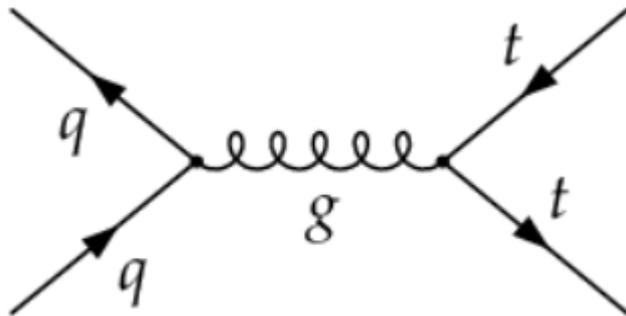


FIG. 1-9. The ratio  $R \equiv \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ . [Compiled by B. Wiik.]

# Evolução “Cor” ↔ Cromodinâmica (QCD)

- 1969 espalhamento inelástico e-p -> fator de escala (Bjorken) partons-quarks
- 1973 Cor como carga (Fritzsch, Leutwyler & Gell-Mann) SU(3)<sub>c</sub>
- 1973 Liberdade Assintótica (Gross, Wilczek & Politzer) -> Cálculo perturbativo
  - Nascimento da QCD -> Teoria de calibre inspirada na QED + Yang-Mills
    - » U(1) -> SU(3)<sub>c</sub> =>  $F_{\mu\nu}$  ->  $G_{\mu\nu}^a$
    - » Mensageiro interage com o campo (não abeliana)



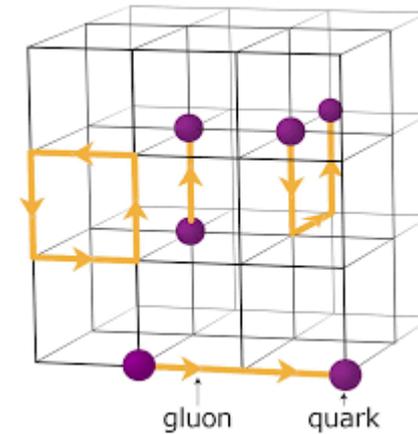
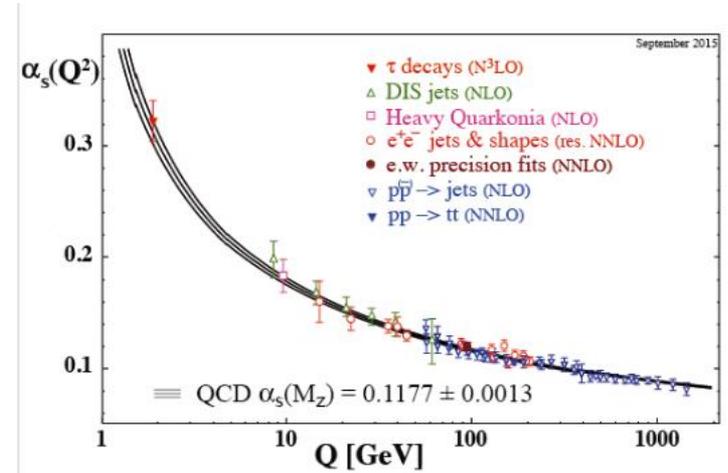
# Interações Fortes -> Cromodinâmica (QCD) -> Quarks

## – Limite perturbativo -> Altas Energias

- Magnitude variável
- $\alpha_s \approx 100 \times \alpha$

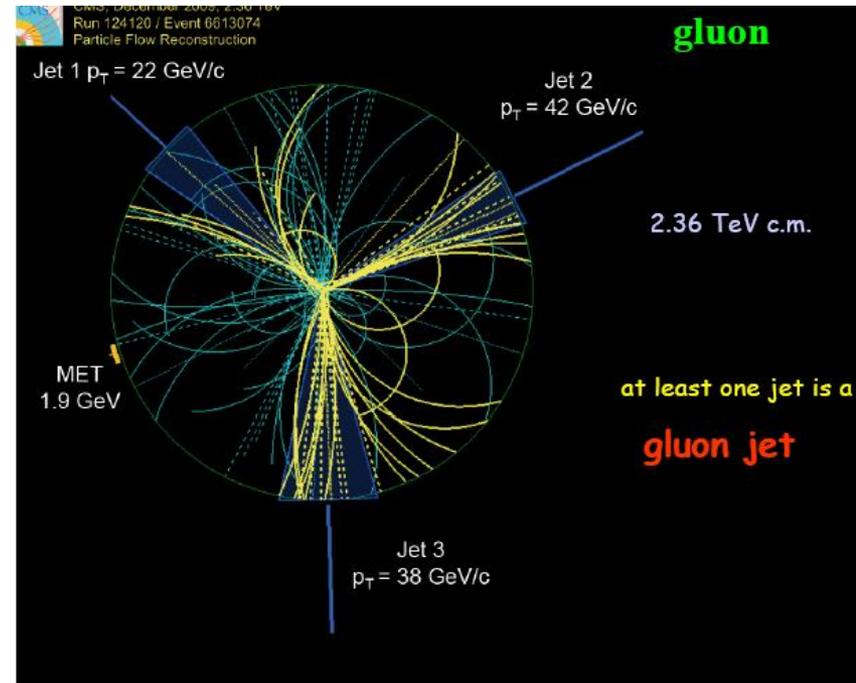
## – Solução? Alternativas?

- QCD na Rede (Lattice)
- Teorias efetivas (ChPT)



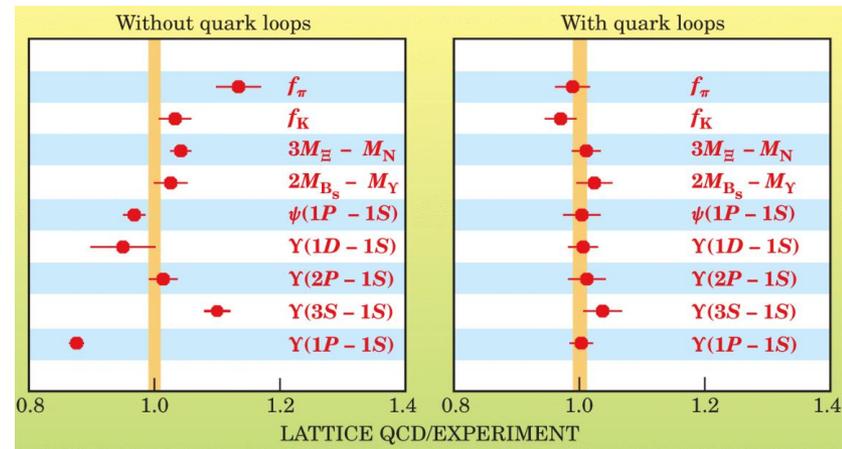
# QCD – Vitórias x Derrotas

- Cálculo perturbativo -> Altas Energias
  - Seções de choque

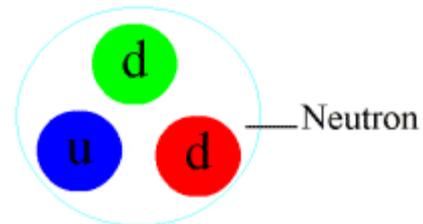
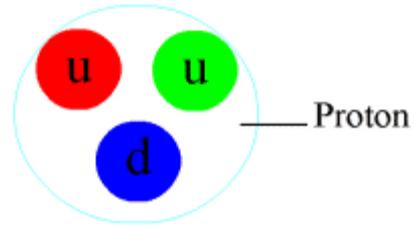


- QCD na Rede

- Confinamento
- Plasma de Quarks e Gluons
- Glueballs



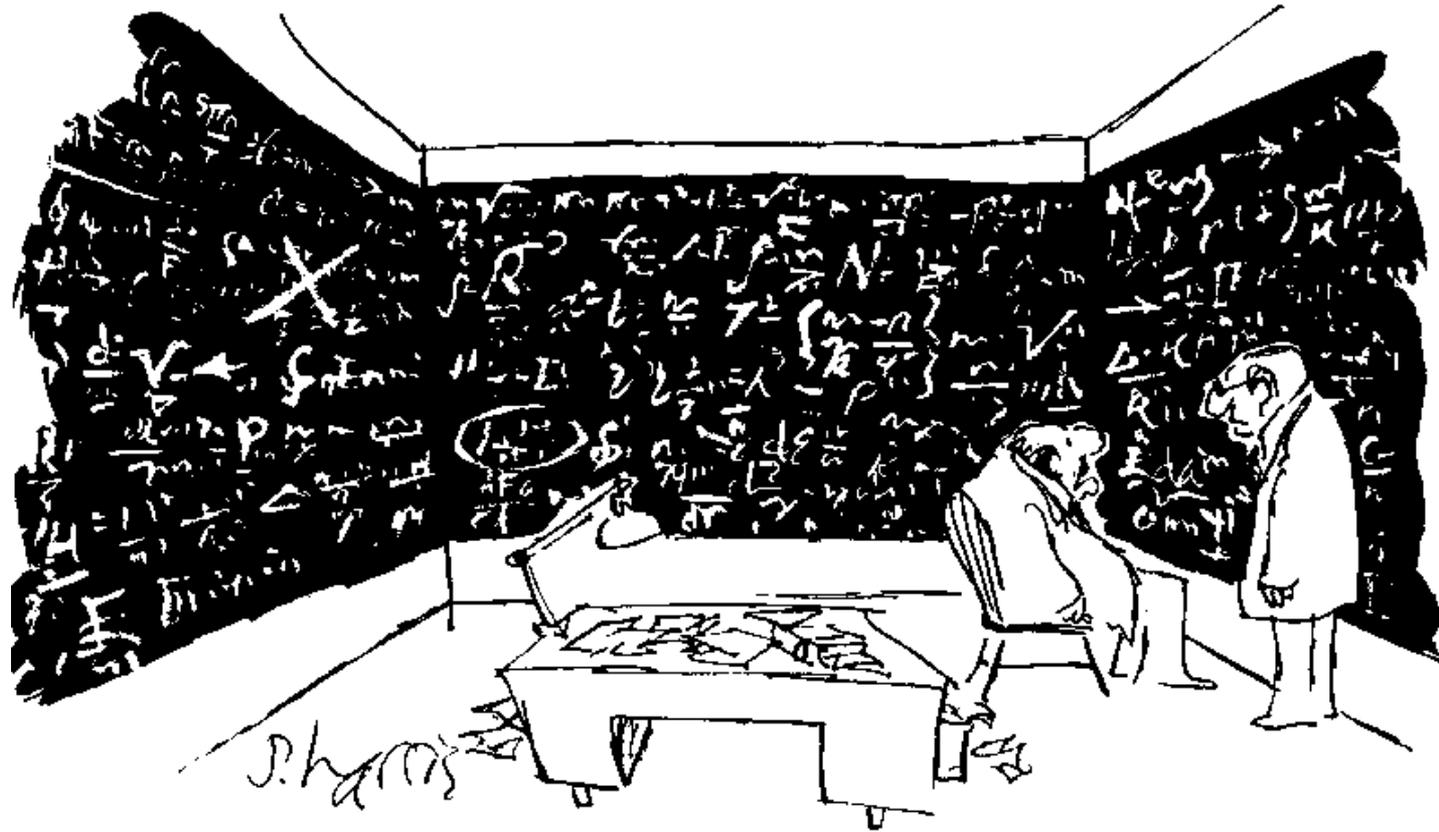
# Prótons e Neutrons??



# Parece confuso??

Qual a solução??

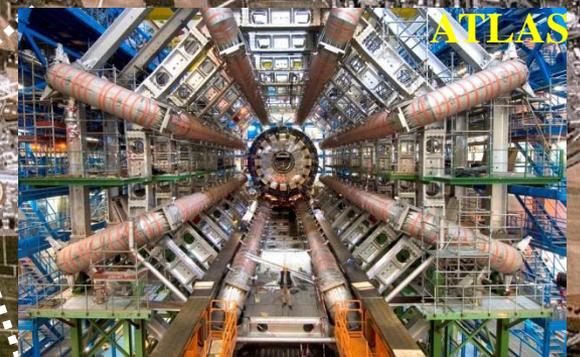
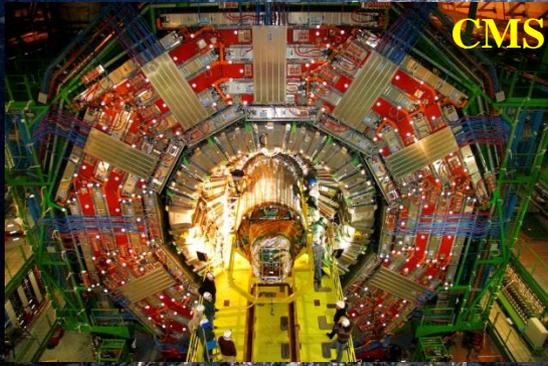
- Estudar a escala de energia TeV
- LHC



“Whatever happened to *elegant* solutions?”

# Os Experimentos do LHC

Os experimentos do LHC formam um conjunto de projetos científicos globais, um dos maiores empreendimentos da física atual.



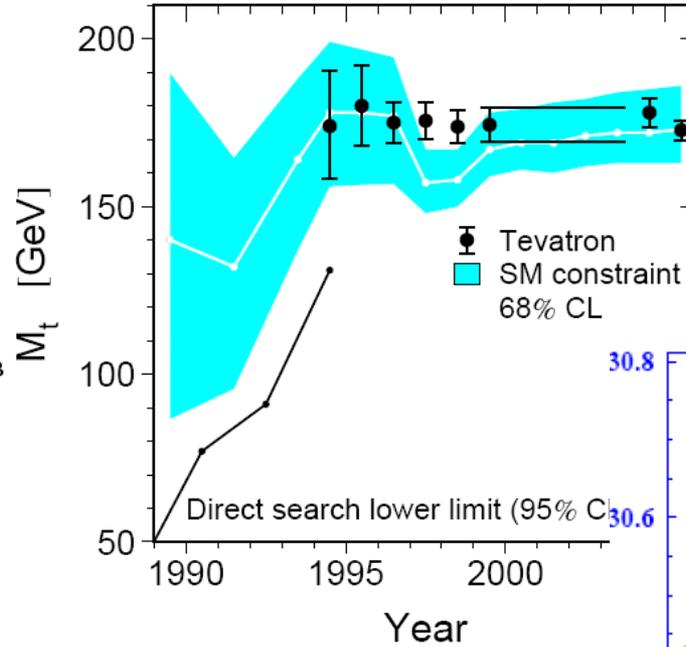


# Backup

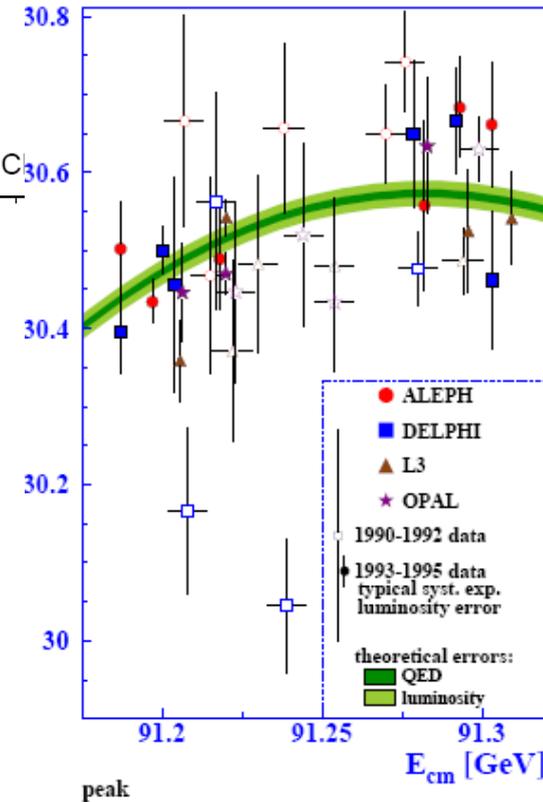
# Vitórias do Modelo Padrão

## Impressionante acordo com dezenas de medidas experimentais

- Incluindo a massa do top
- Produção de quarks pesados
- Jatos
- Assimetrias W, Z
- ...



	Measurement	Fit	$\frac{ O_{meas} - O_{fit} }{\sigma_{meas}}$
$\Delta\alpha_{had}^{(5)}(m_Z)$	$0.02758 \pm 0.00035$	0.02766	0.1
$m_Z$ [GeV]	$91.1875 \pm 0.0021$	91.1874	0.05
$\Gamma_Z$ [GeV]	$2.4952 \pm 0.0023$	2.4957	0.2
$\sigma_{had}^0$ [nb]	$41.540 \pm 0.037$	41.477	1.7
$R_l$	$20.767 \pm 0.025$	20.744	0.9
$A_{fb}^{0,l}$	$0.01714 \pm 0.00095$	0.01640	0.8
$A_l(P_Z)$	$0.1465 \pm 0.0032$	0.1479	0.4
$R_b$	$0.21629 \pm 0.00066$	0.21585	0.8
$R_c$	$0.1721 \pm 0.0030$	0.1722	0.05
$A_{fb}^{0,b}$	$0.0992 \pm 0.0016$	0.1037	2.8
$A_{fb}^{0,c}$	$0.0707 \pm 0.0035$	0.0741	1.1
$A_b$	$0.923 \pm 0.020$	0.935	0.6
$A_c$	$0.670 \pm 0.027$	0.668	0.05
$A_l(SLD)$	$0.1513 \pm 0.0021$	0.1479	1.6
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	$0.2324 \pm 0.0012$	0.2314	0.9
$m_W$ [GeV]	$80.392 \pm 0.029$	80.371	0.7
$\Gamma_W$ [GeV]	$2.147 \pm 0.060$	2.091	1.0
$m_t$ [GeV]	$171.4 \pm 2.1$	171.7	0.1



# Problemas

- **Simetria Interna (calibre): previne anomalias**
- Qualquer massa quebra a simetria

$$\underbrace{SU(3)_C}_{} \times \underbrace{SU(2)_L \times U(1)_Y}_{}$$

CDQ

Eletrofraca



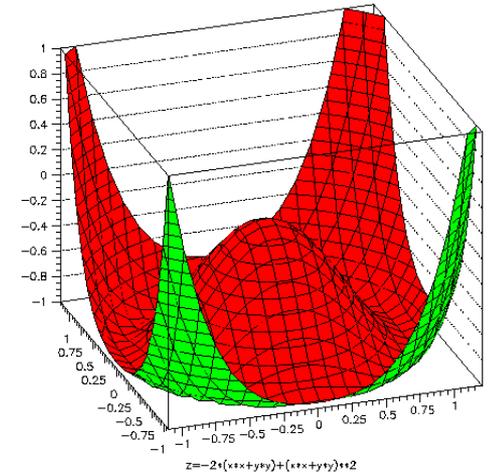
Quebra espontânea EDQ + Fraca → Mecanismo de Higgs

Solução mais econômica

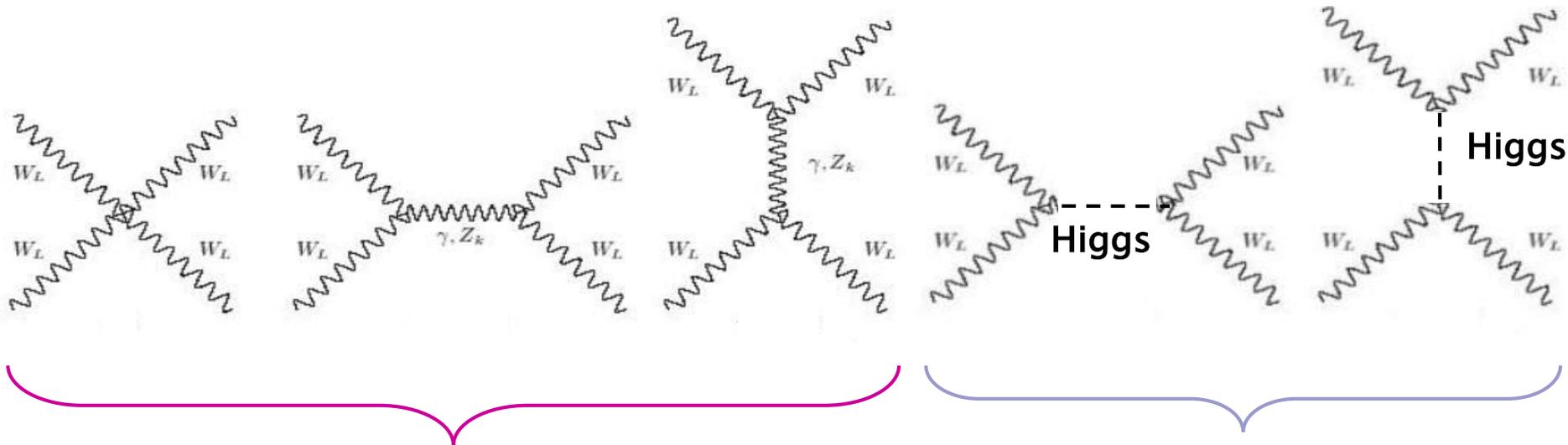
$$V(\phi) = \mu^2 \phi^2 / 2 + \lambda \phi^4 / 4 \quad (\text{vev} \neq 0)$$

- Um único escalar com massa =  $\sqrt{2} \lambda v$
- Termos de massa para  $W^\pm, Z$  ( $\propto v$ )
- Interação com férmions → massa ( $\propto v$ )

Mas...



- **Artificial: forma do potencial, acoplamento, etc.**
- Massas não determinadas.
  - Massa do Higgs  $< 1$  TeV para evitar anomalias

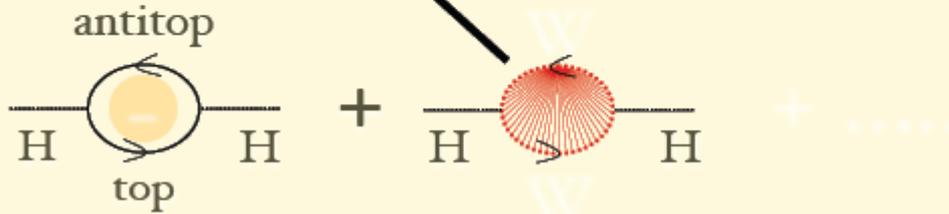


**Violação da unitaridade**  
 $\sigma \sim E^2$

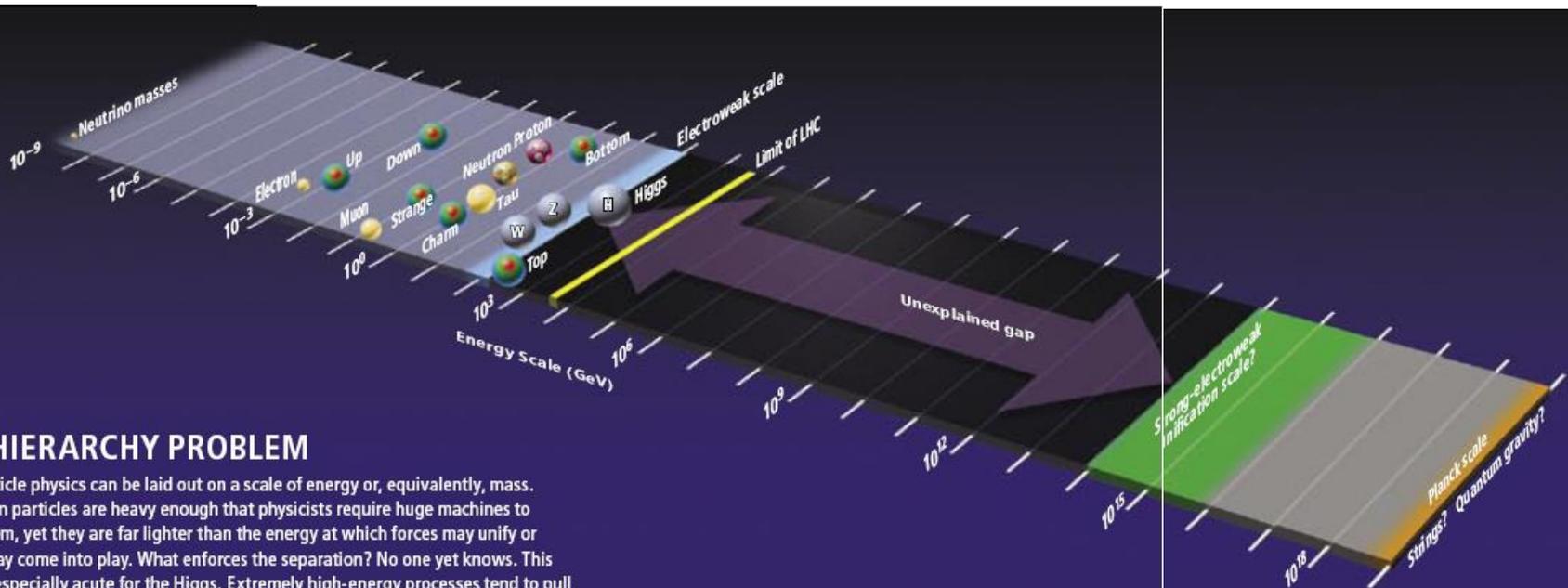
**Restaura a unitaridade**

- Massa do Higgs sofre correções por sua interação
- $m_H < 1\text{TeV}$  exige ajuste preciso (artificial)  $\Lambda \approx 10^{19}\text{ GeV}$
- Problema da hierarquia

$$m_H^2 = m_0^2 - \frac{6G_F}{\sqrt{2}\pi^2} \left( m_t^2 - \frac{1}{2}m_W^2 - \frac{1}{4}m_Z^2 - \frac{1}{4}m_H^2 \right) \Lambda^2 \sim m_0^2 - (115\text{GeV})^2 \left( \frac{\Lambda}{400\text{GeV}} \right)^2$$



$\Lambda =$  scale up to which the SM is valid

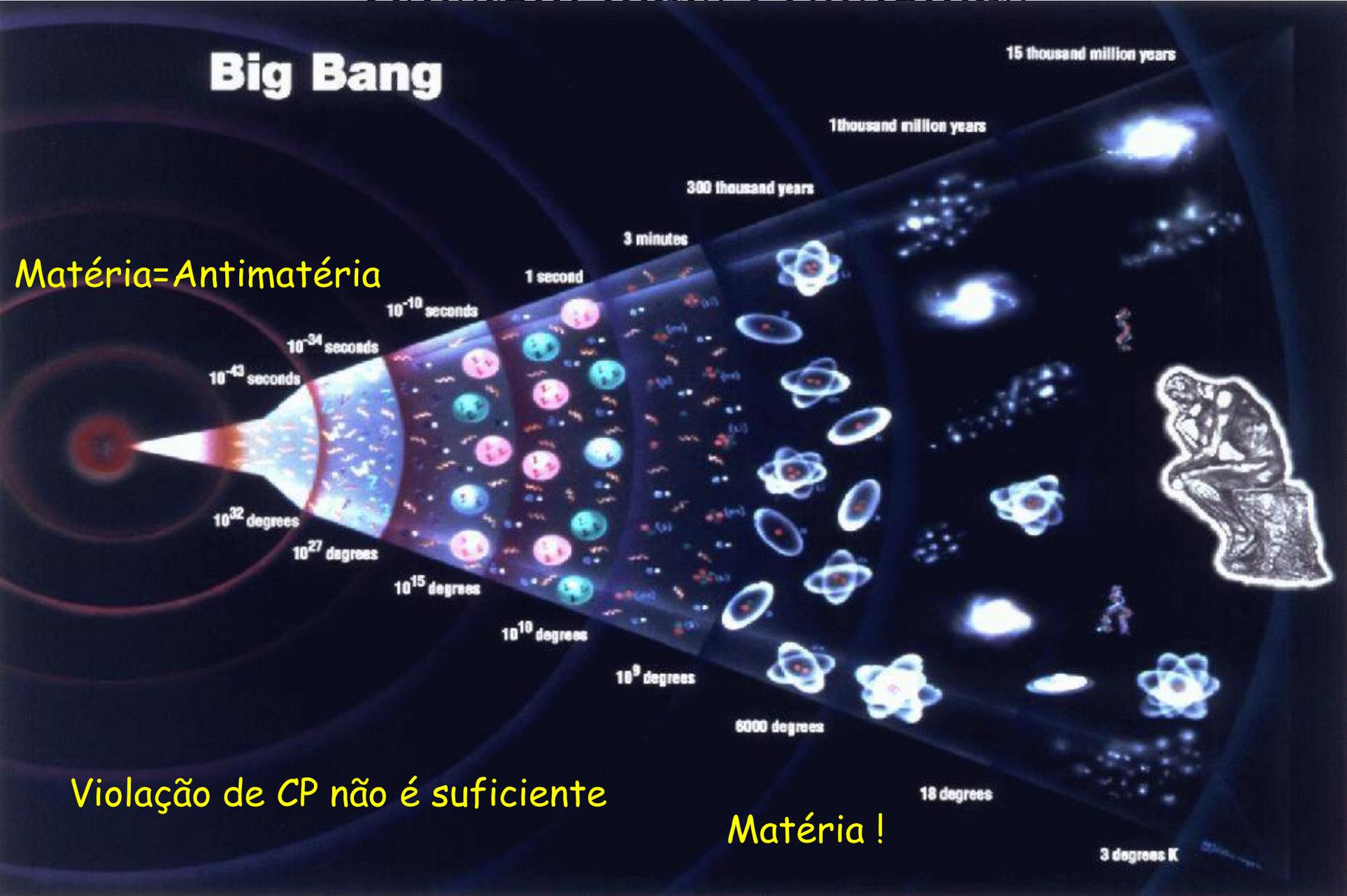


## THE HIERARCHY PROBLEM

All of particle physics can be laid out on a scale of energy or, equivalently, mass. The known particles are heavy enough that physicists require huge machines to create them, yet they are far lighter than the energy at which forces may unify or gravity may come into play. What enforces the separation? No one yet knows. This puzzle is especially acute for the Higgs. Extremely high-energy processes tend to pull its mass far above 1 TeV. What holds it down?

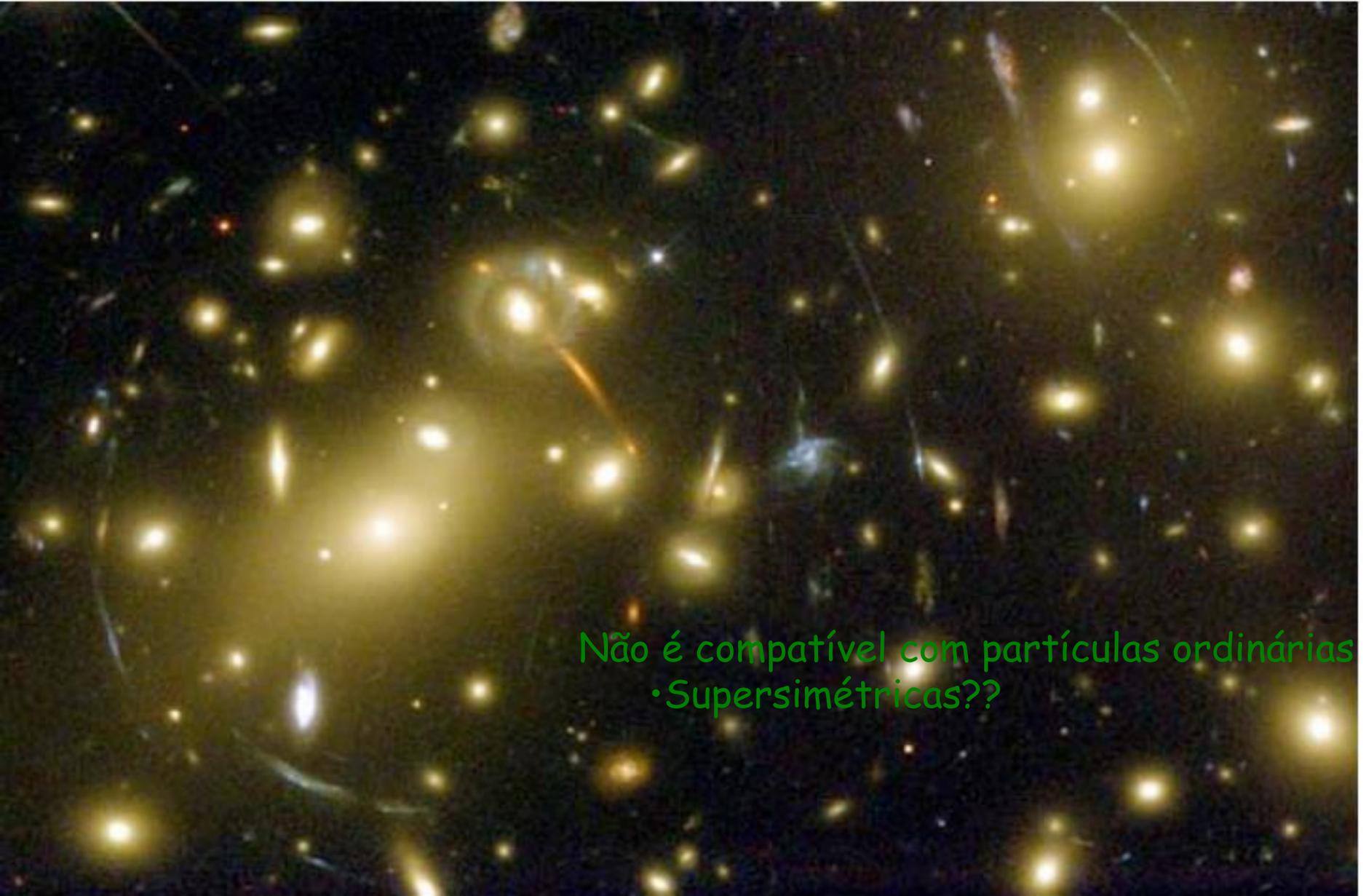
# Existem mais Problemas

## Big Bang





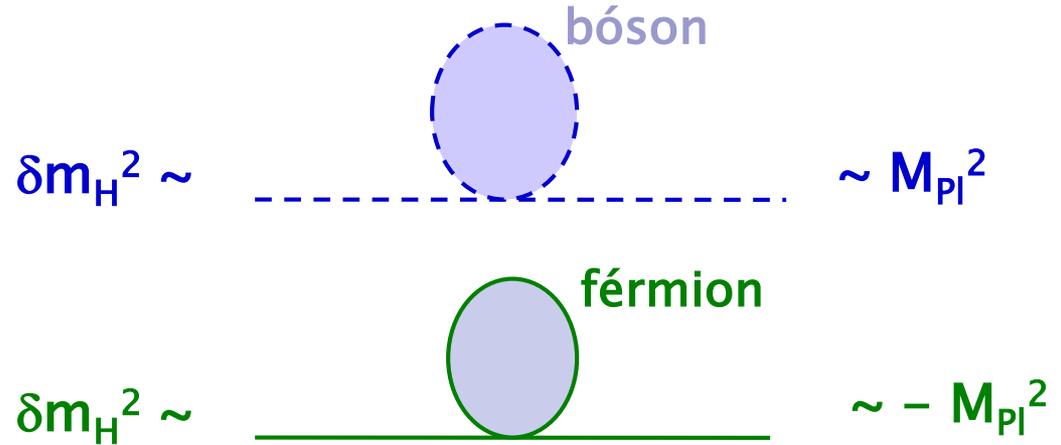
# Matéria Escura



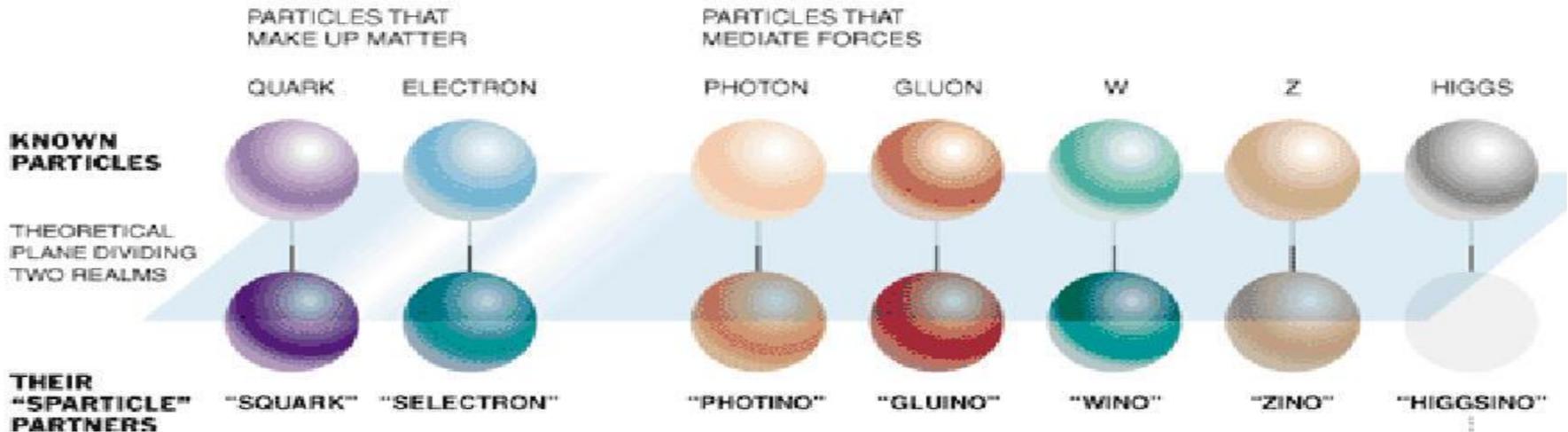
Não é compatível com partículas ordinárias  
• Supersimétricas??

# Como resolver esse dilema???

- Supersimetria
  - Perfeita simetria
    - férmions e bósons
    - cancelamento
  - Novas partículas

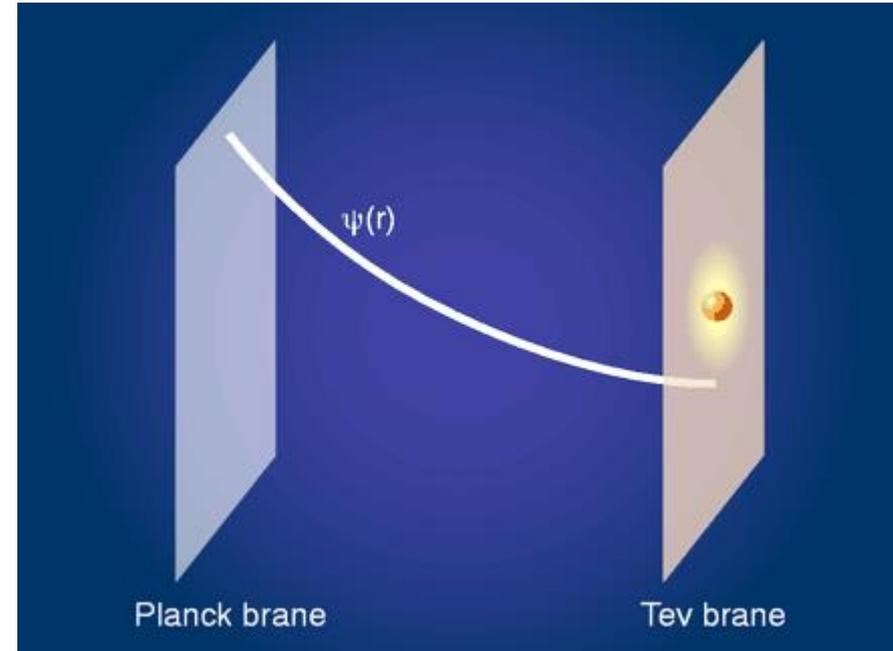


## superparticles



## Dimensões extras

- Motivação - Supercordas
  - Gravitação  $\Leftrightarrow$  D.E.
- Escala de unificação == Eletrofraca
- Muitos modelos
  - Muitos efeitos
  - Ressonâncias KK
    - Cordas
    - Gráviton
  - Mini-buracos negros
  - Energia perdida
  - ...



# Sistema de Unidades

**SI padrão não é adequado para os sistemas microscópicos**

**$M=kg, L=m, t=s \Rightarrow E=J$**

• **Sistema Natural  $\hbar=c=1$**

**Grandezas fundamentais  $E=eV, v=c, \text{mom. ang.} = \hbar$**

**$1eV = 1.6 \times 10^{-19} J$**

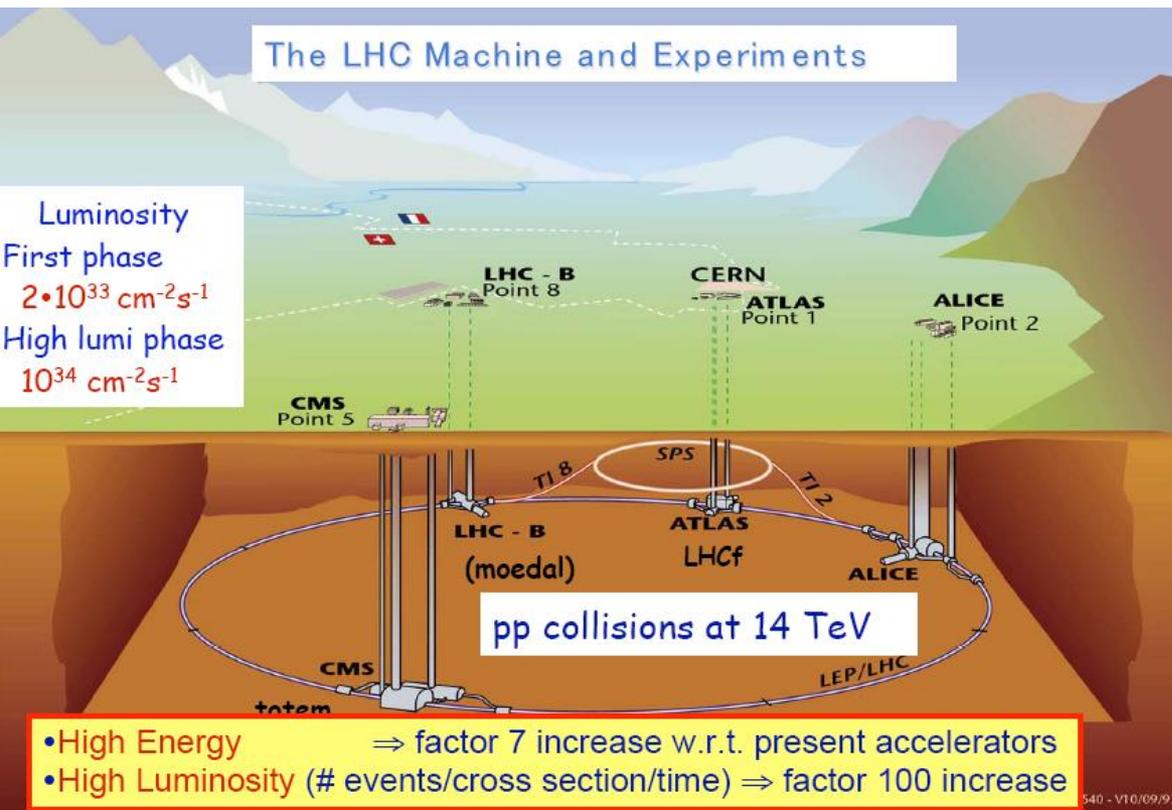
**$M_p = 1.6726219 \times 10^{-27} kg = 0.938 GeV$**

**$M_{top} = 175 GeV$**

**Raios Cósmicos  $\approx 10^{20} eV$  (Lab)**

**Aceleradores  $\approx 10^{12} eV$  (CM)**

# The Large Hadron Collider



## Large

- 27 km de circunferência

## Hadron

- prótons
- ions

## Collider

- ~ 7 x mais energia
- ~ 100 x mais luminosidade
- Comparado ao Tevatron

## Próton - Próton

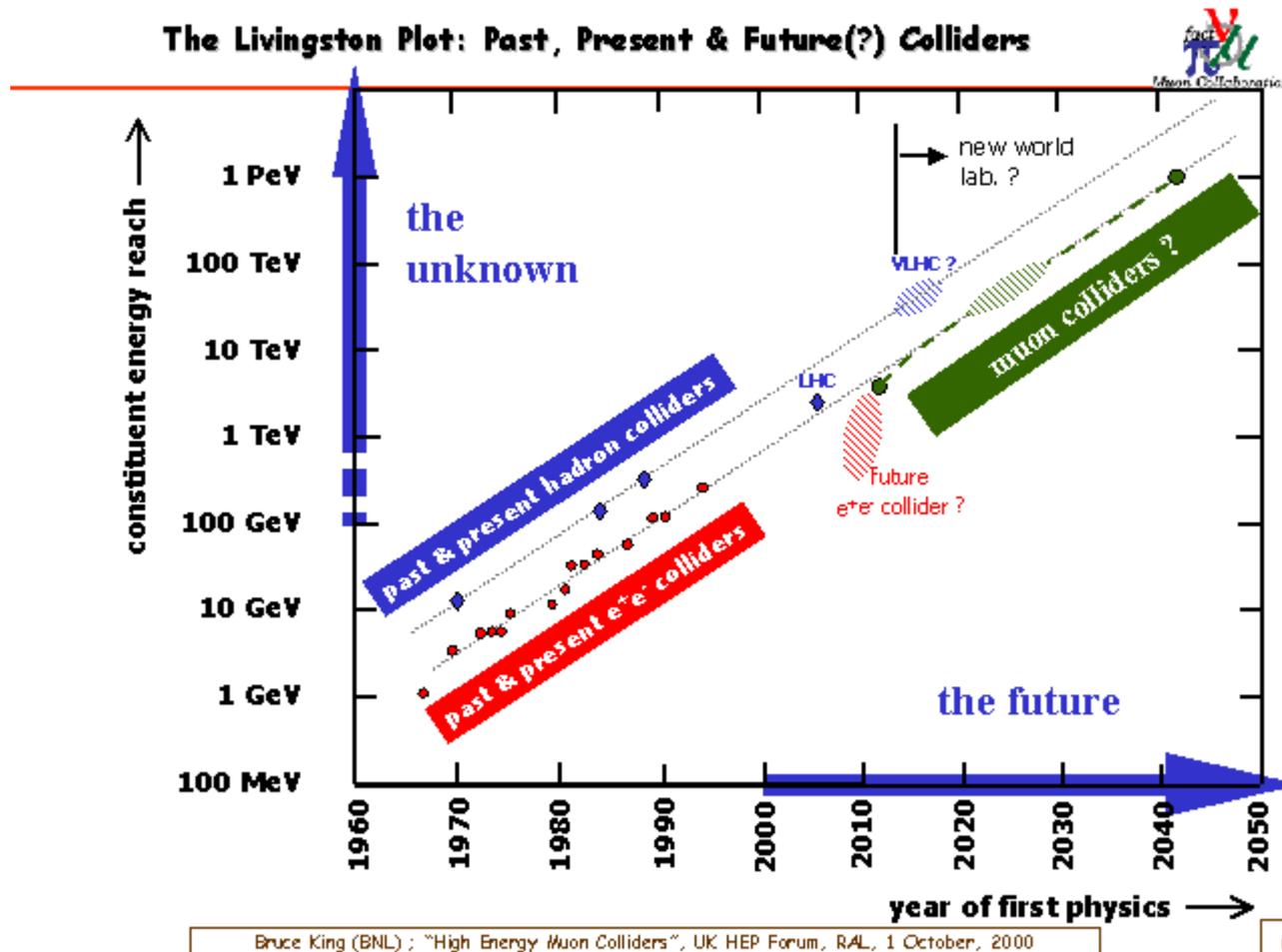
a  $\sqrt{s} = 14 \text{ TeV}^{**}$  (\*\*a partir de 2019/20)

## Luminosidade ~

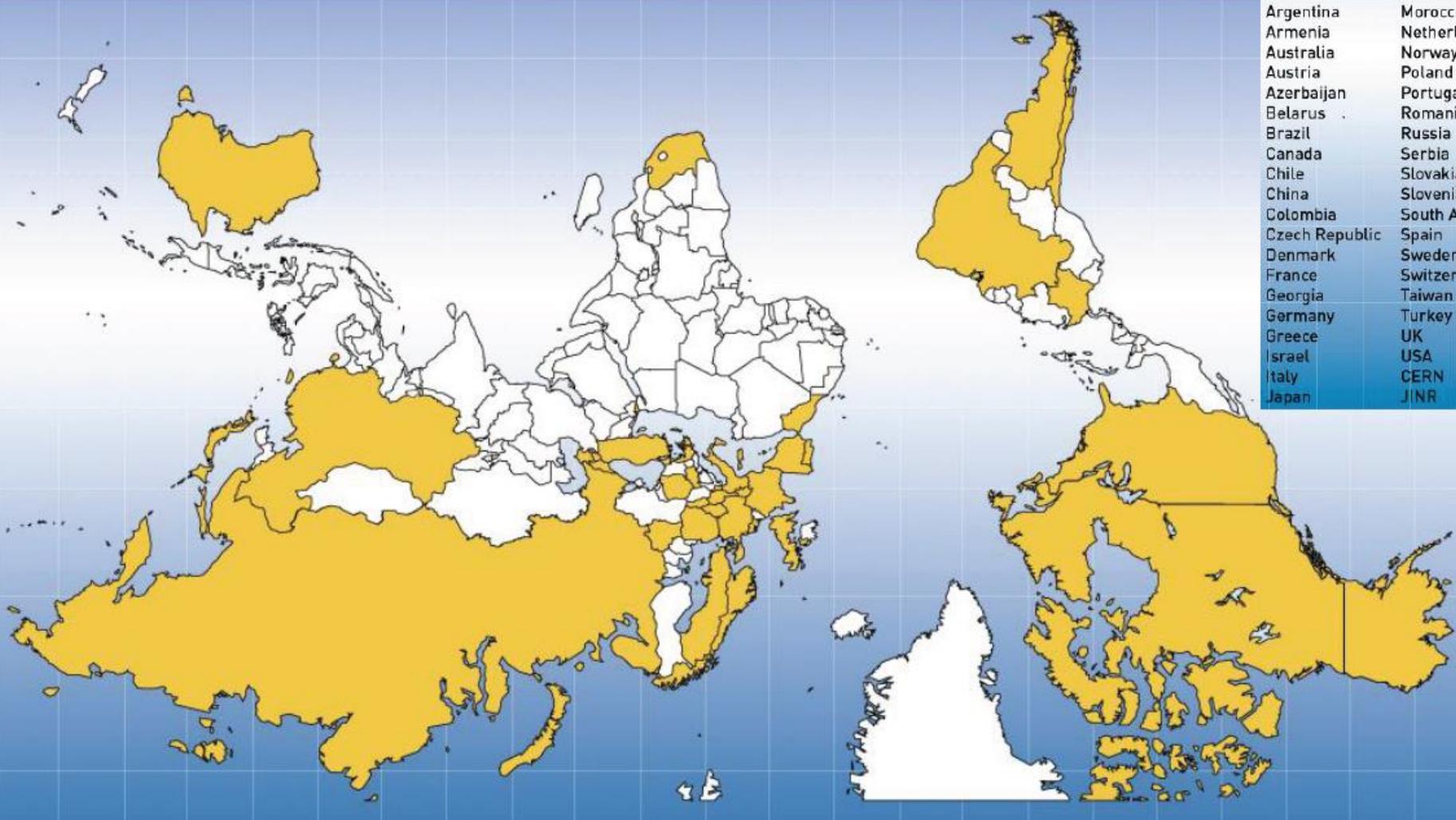
~100 fb<sup>-1</sup> / expt / Ano\*\* (\*\*a partir de 2017/18)

# Aceleradores Lineares x Circulares II

- Já vimos que a energia disponível para produção de novas partículas  $\sqrt{2E} \Leftrightarrow 2E$  (alvo estacionário x colisão frontal)
- Dai a utilização cada vez mais frequente de colisores de partículas

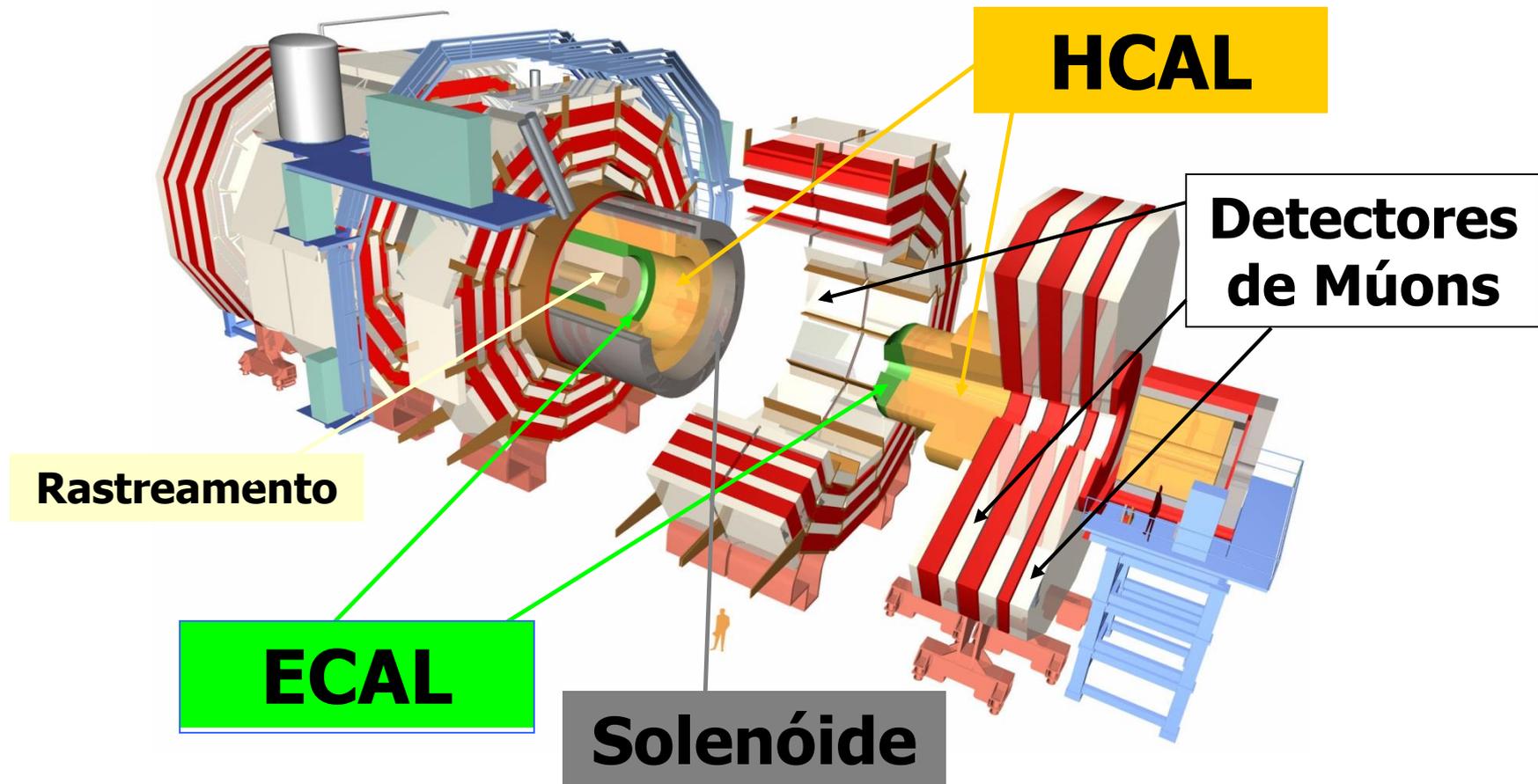


# A Colaboração CMS

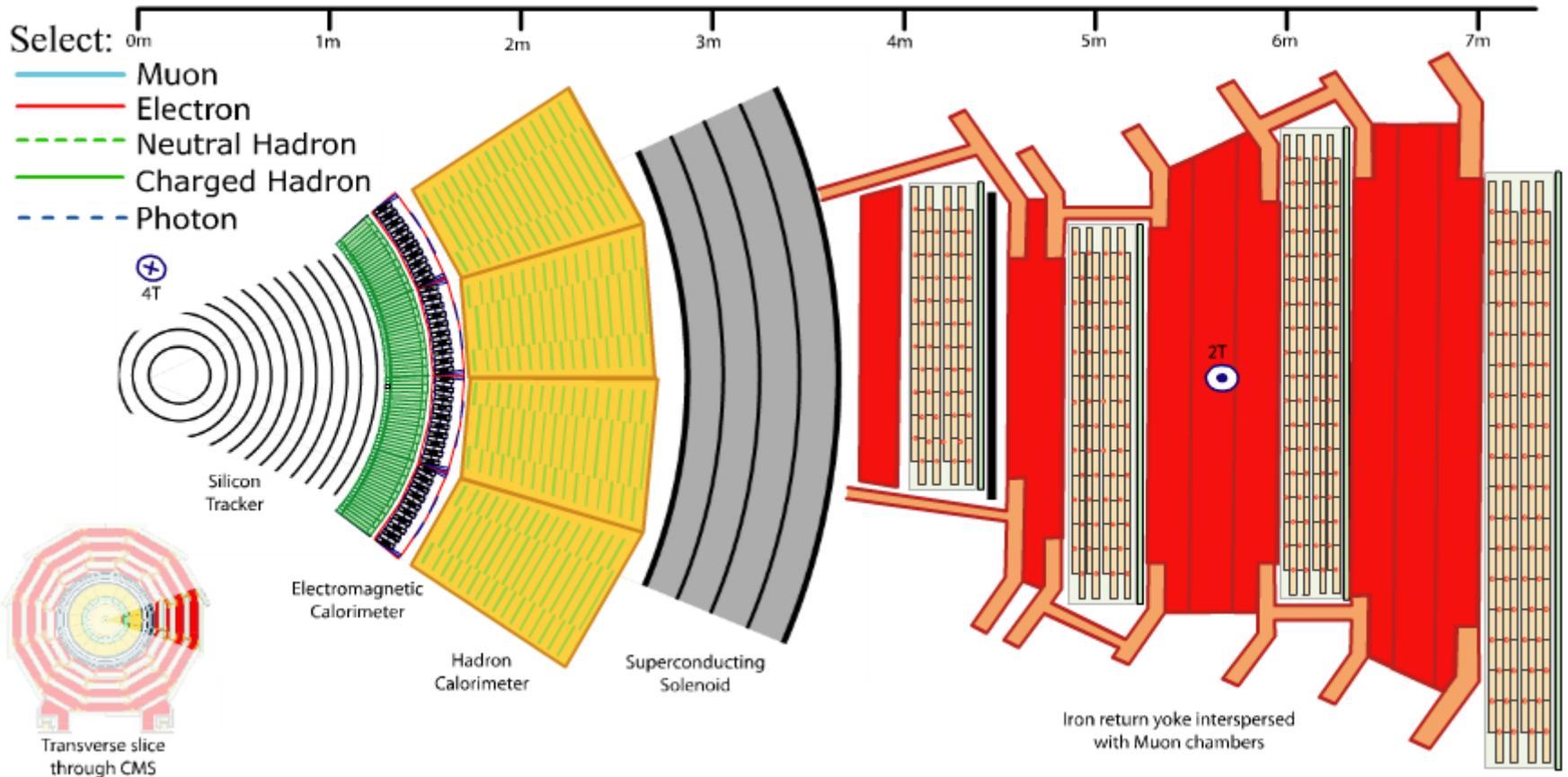


Argentina	Morocco
Armenia	Netherlands
Australia	Norway
Austria	Poland
Azerbaijan	Portugal
Belarus	Romania
Brazil	Russia
Canada	Serbia
Chile	Slovakia
China	Slovenia
Colombia	South Africa
Czech Republic	Spain
Denmark	Sweden
France	Switzerland
Georgia	Taiwan
Germany	Turkey
Greece	UK
Israel	USA
Italy	CERN
Japan	JINR

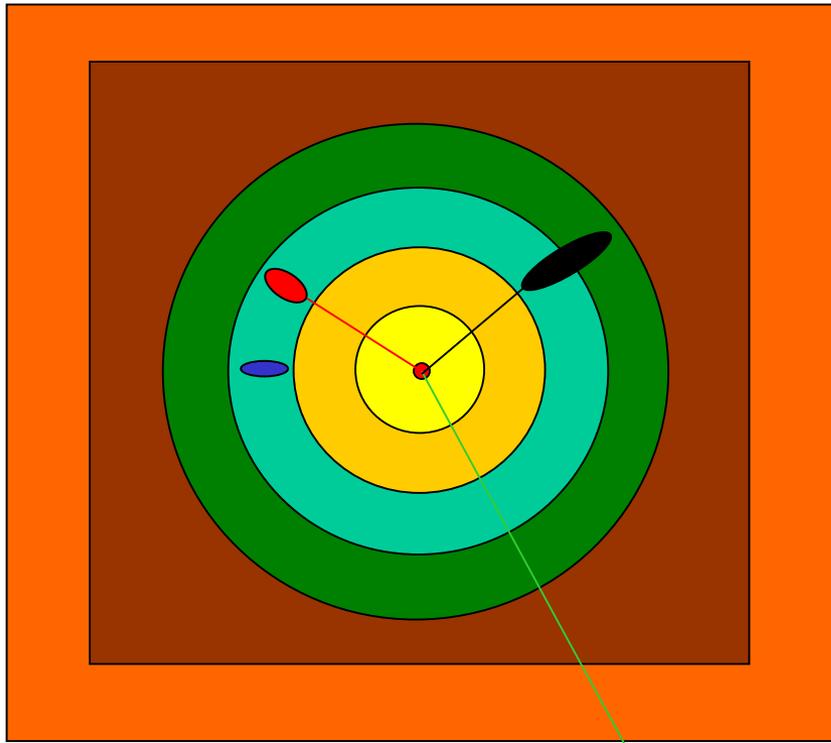
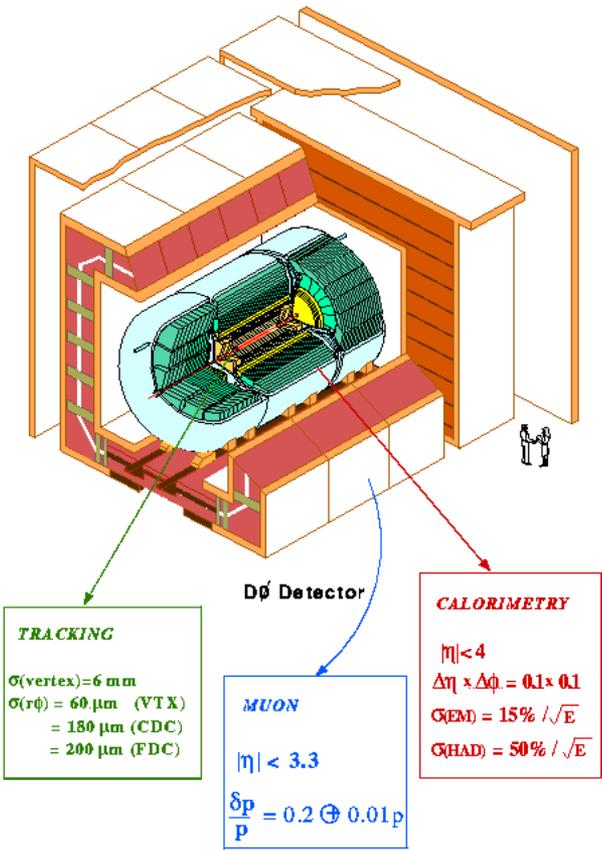
# O Detector CMS



# Corte Transversal do Detector



# Detector Típico em Colisores



# Jatos de quarks e glúons

