

Espectroscopia, simetria $SU(3)$ e os quarks

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Núcleons (p,n) e Isospin ($I = \frac{1}{2}$)

- prótons e nêutrons – mesmo spin ($J = \frac{1}{2}$)
- interação forte (no interior dos núcleos) não depende das massas nem das cargas elétricas
- prótons e nêutrons, genericamente conhecidos como núcleons, só revelados pelas interações eletromagnéticas (sensíveis à carga elétrica) ou pelas interações fracas (decaimento do nêutron)
- interações no interior do núcleo são denominadas interações fortes residuais ou nucleares
- têm a mesma intensidade para qualquer par de núcleons, próton–próton, próton–nêutron ou nêutron–nêutron

- Heisenberg (1932) : ambos constituem auto estados degenerados do hamiltoniano que descreve essas interações fortes
- auto estados de uma grandeza análoga ao spin $\frac{1}{2}$ do elétron ou do isospin (I) $\frac{1}{2}$

$$I_1 = \frac{1}{2}\sigma_1 \quad I_2 = \frac{1}{2}\sigma_2 \quad I_3 = \frac{1}{2}\sigma_3$$

- núcleon: dubleto de auto estados simultâneos de I^2 e I_3

	I_3	dubleto	carga (Q)	massa (MeV)
núcleon ($I = 1/2$)	+1/2	$p = 1/2, 1/2\rangle$	1	938,3
	-1/2	$n = 1/2, -1/2\rangle$	0	939,5

Isospin

- conservado nas interações fortes
- interações fortes não distinguem membros do dubleto

$$[H_{\text{forte}}, I^2] = [H_{\text{forte}}, I_3] = 0$$

- não conservado nas interações eletromagnéticas e fracas

$$[H_{\text{em}}, I^2] \neq 0 \quad \text{e} \quad [H_{\text{fraca}}, I_3] \neq 0$$

Simetria de Isospin

- interações fracas e eletromagnéticas não exibem a simetria de isospin
- baixas energias: as interações fracas são bem menos intensas (0.001%) do que as interações eletromagnéticas, e essas, por sua vez, bem menos intensas (1%) do que as interações fortes
- simetria aproximada
- hádrons: as partículas sujeitas às interações fortes residuais
 - bárions: spin semi-inteiro
 - mésons: spin inteiro

Tripleto de píons

□ Píons (π^+ , π^- , π^0) : Isospin $I = 1$

	I_3	triplete	carga (Q)	massa (MeV)
píon ($I = 1$)	+1	$\pi^+ = 1, +1\rangle$	1	139.6
	0	$\pi^0 = 1, 0\rangle$	0	135
	-1	$\pi^- = 1, -1\rangle$	-1	139.6

- emulsões nucleares (raios cósmicos - Lattes et al. 1947)

Partículas estranhas e ressonâncias

□ káons (K^+ , K^0) e lambda (Λ^0)

• $\pi^- + p \rightarrow \Lambda^0 + K^0 +$ (forte – 10^{-23} s) – produção

• decaimentos fracos (10^{-10} s)

$\Lambda^0 \rightarrow p + \pi^-$ (fraco)

$K^0 \rightarrow \pi^+ + \pi^-$ (fraco)

– câmara de bolhas (Glaser – Berkeley 1952)

– Cosmotron – 2.2 GeV (BNL 1953)

□ ressonâncias: delta (Δ^+ , Δ^- , Δ^0) e rho (ρ^+ , ρ^- , ρ^0)

– Bevatron – 6.5 GeV (Berkeley 1954)

Estranheza

□ Gell–Mann, Nakano e Nishijima (1953)

$$\left\{ \begin{array}{l} \Delta S = 0 \quad (\text{interações fortes e eletromagnéticas}) \\ |\Delta S| = 1 \quad (\text{interações fracas na presença de partículas estranhas}) \end{array} \right.$$

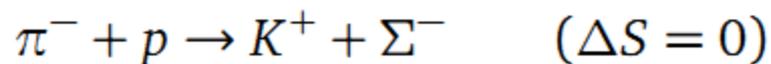
$S = +1$ (káons)

$S = 0$ (núcleons, píons)

$S = -1$ (lambdas, sigmas)

$S = -2$ (xi)

Desse modo, explicava-se por que a reação forte



poderia ocorrer, e as reações

$$\left\{ \begin{array}{ll} \pi^- + p \rightarrow K^0 + n & (\Delta S = 1) \\ \pi^- + p \rightarrow K^- + \Sigma^+ & (\Delta S = -2) \\ \pi^- + p \rightarrow \pi^- + \Sigma^+ & (\Delta S = -1), \end{array} \right.$$

apesar de não violarem a lei de conservação de carga, não ocorreriam.

Multipletos de Isospin

- quadrupleteo ($I = 3/2$): ($\Delta^{++}, \Delta^+, \Delta^0, \Delta^-$) – bárions
- tripletos ($I = 1$): ($\Sigma^+, \Sigma^0, \Sigma^-$) – bárions, (ρ^+, ρ^0, ρ^-) – mésons
- dobletos ($I = 1/2$): (Ξ^0, Ξ^-) – bárions, (K^+, K^0) – mésons
- singleto ($I = 0$): (Λ^0) – bárion

Fórmula de Gell-Mann/Nishijima

$$Q = I_3 + (B+S)/2 = I_3 + Y/2$$

- Q (carga)
- B (nº bariônico)
 - número quântico aditivo
 - lei de conservação universal: número de bárions menos o número de antibárions permanece constante
 - estabilidade do próton
- $Y = B + S$ (hipercarga)

Grupos

$\{a, b, c, \dots, e, \dots\}$ e operação $(.)$

$$\left\{ \begin{array}{l} a \cdot b = c \\ (a \cdot b) \cdot c = a \cdot (b \cdot c) \\ e \cdot a = a \\ a^{-1} \cdot a = e \end{array} \right. \begin{array}{l} \text{(fechamento)} \\ \text{(associatividade)} \\ \text{(identidade)} \\ \text{(inverso)} \end{array}$$

- grupo das rotações próprias
- matrizes ortogonais ($\det = 1$)
- representações matriciais

Grupo $Su(2)$

- representação unitária ($\det = 1$) do grupo das rotações

$$U = e^{i \theta_\alpha G_\alpha} \quad (\alpha = 1, 2, 3)$$

θ_α – parâmetros

G_α – geradores

- regras de comutação $[G_\alpha, G_\beta] = i \epsilon_{\alpha\beta\gamma} G_\gamma$

$$[S_\alpha, S_\beta] = i \epsilon_{\alpha\beta\gamma} S_\gamma$$

- spin $\frac{1}{2}$ ou matrizes de Pauli – geradores da representação unitária fundamental de $SU(2)$

Composição de representações

$$j_1: |1/2, +1/2\rangle_1 \quad \text{e} \quad |1/2, -1/2\rangle_1$$

$$j_2: |1/2, +1/2\rangle_2 \quad \text{e} \quad |1/2, -1/2\rangle_2$$

$$\text{triplete} \left\{ \begin{array}{l} |1, +1\rangle = |1/2, +1/2\rangle_1 |1/2, +1/2\rangle_2 \\ |1, 0\rangle = \frac{1}{\sqrt{2}} \left[|1/2, +1/2\rangle_1 |1/2, -1/2\rangle_2 + |1/2, -1/2\rangle_1 |1/2, +1/2\rangle_2 \right] \\ |1, -1\rangle = |1/2, -1/2\rangle_1 |1/2, -1/2\rangle_2 \end{array} \right.$$

$$\text{singlete} \left\{ |0, 0\rangle = \frac{1}{\sqrt{2}} \left[|1/2, +1/2\rangle_1 |1/2, -1/2\rangle_2 - |1/2, -1/2\rangle_1 |1/2, +1/2\rangle_2 \right] \right.$$

$$1/2 \otimes 1/2 = 1 \oplus 0 \quad \text{ou} \quad 2 \otimes 2 = 3 \oplus 1$$

Decomposição em soma direta

- Autoestados simultâneos de S^2 e S_z são os estados básicos da representação fundamental do grupo $SU(2)$, a partir dos quais todos os outros estados, associados a representações de ordens superiores, podem ser construídos

$$\left\{ \begin{array}{l} 1 \otimes 1/2 = 3/2 \oplus 1/2 \quad \text{ou} \quad 3 \otimes 2 = 4 \oplus 2 \\ 3/2 \otimes 1 = 5/2 \oplus 3/2 \oplus 1/2 \quad \text{ou} \quad 4 \otimes 3 = 6 \oplus 4 \oplus 2 \\ 1/2 \otimes 1/2 \otimes 1/2 = 3/2 \oplus 1/2 \oplus 1/2 \quad \text{ou} \quad 2 \otimes 2 \otimes 2 = 4 \oplus 2 \oplus 2 \end{array} \right.$$

Espalhamento pión-núcleoon

□ $I=1$ (píon) $I= \frac{1}{2}$ (núcleon)

□

$$\left\{ \begin{array}{l} |3/2, +3/2\rangle = \pi^+ p \\ |3/2, +1/2\rangle = \sqrt{\frac{1}{3}} \pi^+ n + \sqrt{\frac{2}{3}} \pi^0 p \\ |3/2, -1/2\rangle = \sqrt{\frac{1}{3}} \pi^- p + \sqrt{\frac{2}{3}} \pi^0 n \\ |3/2, -3/2\rangle = \pi^- n \\ |1/2, +1/2\rangle = \sqrt{\frac{2}{3}} \pi^+ n - \sqrt{\frac{1}{3}} \pi^0 p \\ |1/2, -1/2\rangle = -\sqrt{\frac{2}{3}} \pi^- p + \sqrt{\frac{1}{3}} \pi^0 n \end{array} \right.$$

reciprocamente

combinações	estados
$\pi^+ p$	$ 1, +1\rangle 1/2, +1/2\rangle = 3/2, +3/2\rangle$
$\pi^- n$	$ 1, -1\rangle 1/2, -1/2\rangle = 3/2, -3/2\rangle$
$\pi^+ n$	$ 1, +1\rangle 1/2, -1/2\rangle = \sqrt{\frac{1}{3}} 3/2, +1/2\rangle + \sqrt{\frac{2}{3}} 1/2, +1/2\rangle$
$\pi^- p$	$ 1, -1\rangle 1/2, +1/2\rangle = \sqrt{\frac{1}{3}} 3/2, -1/2\rangle - \sqrt{\frac{2}{3}} 1/2, -1/2\rangle$
$\pi^0 p$	$ 1, 0\rangle 1/2, +1/2\rangle = \sqrt{\frac{2}{3}} 3/2, +1/2\rangle - \sqrt{\frac{1}{3}} 1/2, +1/2\rangle$
$\pi^0 n$	$ 1, 0\rangle 1/2, -1/2\rangle = \sqrt{\frac{2}{3}} 3/2, -1/2\rangle + \sqrt{\frac{1}{3}} 1/2, -1/2\rangle$

Supondo que o estado de isospin $3/2$ seja uma ressonância (Δ) que domine as reações

$$\left\{ \begin{array}{l} \pi^+ p \rightarrow \pi^+ p \\ \pi^- p \rightarrow \pi^0 n \\ \pi^- p \rightarrow \pi^- p \end{array} \right.$$

Bruckner sugeriu que as respectivas taxas de produção seriam proporcionais a

$$|\langle \pi^+ p | \pi^+ p \rangle|^2 = 1$$

$$|\langle \pi^0 n | \pi^- p \rangle|^2 = 2/9$$

$$|\langle \pi^- p | \pi^- p \rangle|^2 = 1/9$$

9:2:1 – compatível com resultados de Fermi

Modelo de Sakata

□ Sakata (1956) – SU(3)

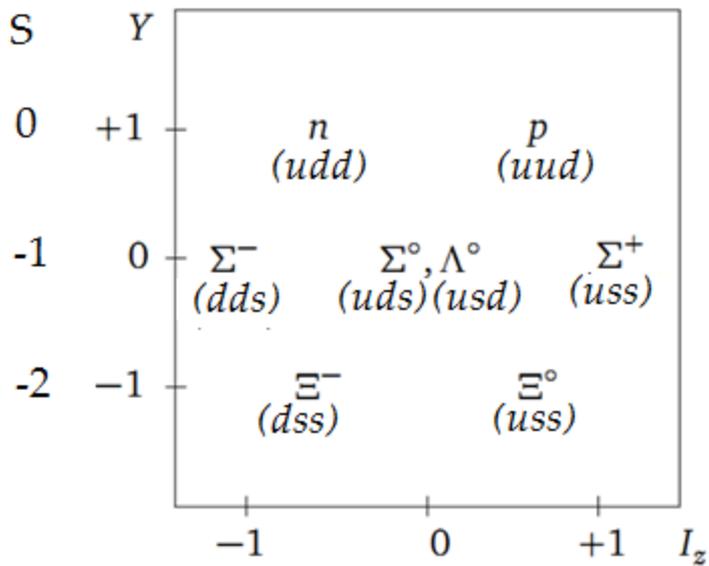
(p, n, Λ^0) e $(\bar{p}, \bar{n}, \bar{\Lambda}^0)$ – tripletos fundamentais

- mésons (1 partícula + 1 antipartícula)
- bárions (2 partículas + 1 antipartícula) ou (1 partícula + 2 antipartículas)

Octetos de Gell-Mann (1960)

bárions

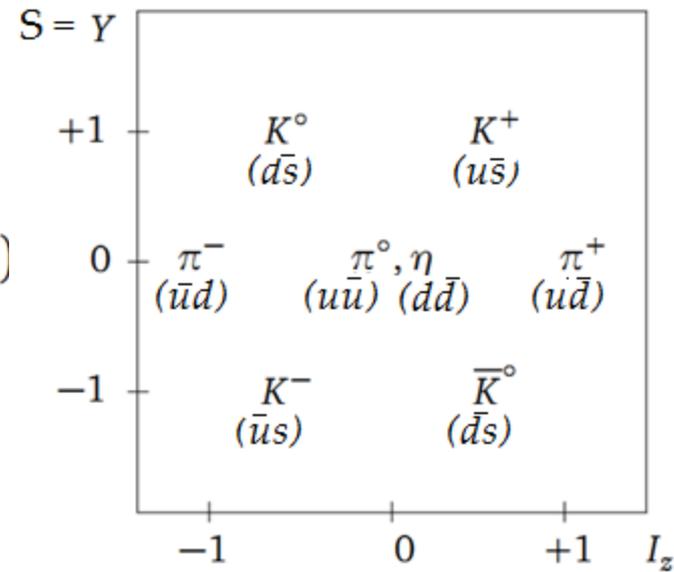
B=1



$(J^P) = (1/2^+)$

mésos

B=0

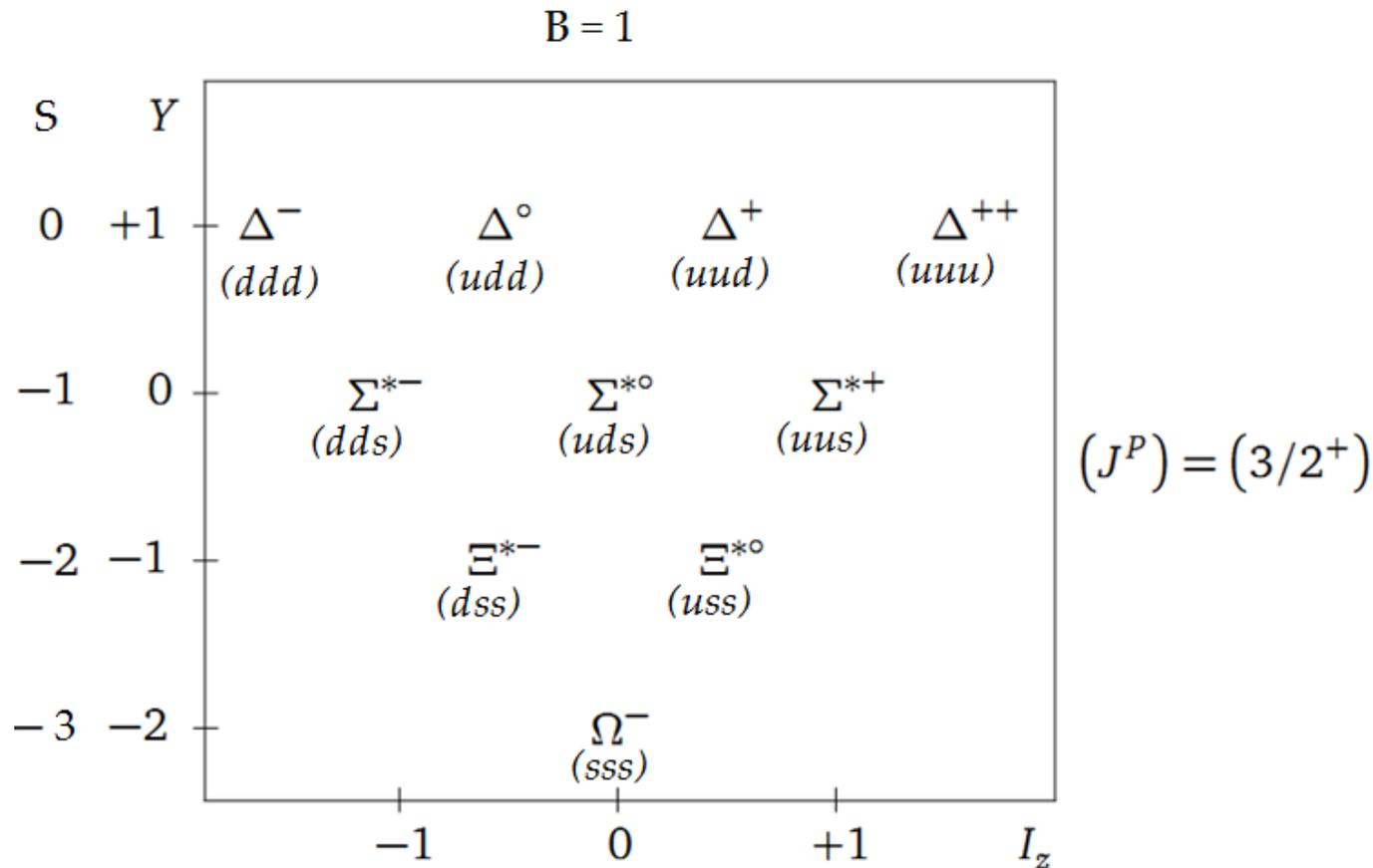


$(J^P) = (0^-)$

η (547.8 MeV)

– descoberto apenas em 1961

Decuplete de bárions



Ω^- (1672 MeV) – descoberto apenas em 1964

Quarks: grupo SU(3) de sabor

$$U = \exp \left\{ i\alpha_k \frac{\lambda_k}{2} \right\}$$

- estados fundamentais:
tripleto de quarks (u, d, s) de spin $\frac{1}{2}$
- 8 parâmetros : $\{\alpha_k \mid k = 1, 2, \dots, 8\}$

$$\left\{ \begin{array}{l} 3 \otimes \bar{3} = 8 \oplus 1 \quad (\text{mésos}) \\ 3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1 \quad (\text{bárions}) \end{array} \right.$$

8 geradores: $\{\lambda_k \mid k = 1, 2, \dots, 8\}$

$$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} \quad \lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

$$\lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \quad \lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

$$\text{tr } \lambda_k \lambda_j = 2\delta_{kj}$$

$$[\lambda_i, \lambda_j] = 2i f_{ijk} \lambda_k$$

$$f_{123} = 1$$

$$f_{147} = 1/2$$

$$f_{156} = -1/2$$

$$f_{246} = 1/2$$

$$f_{257} = 1/2$$

$$f_{345} = 1/2$$

$$f_{367} = -1/2$$

$$f_{458} = \sqrt{3}/2$$

$$f_{678} = \sqrt{3}/2$$

Quarks: grupo SU(3) de sabor

	<i>quarks</i>			<i>antiquarks</i>		
	<i>u</i>	<i>d</i>	<i>s</i>	\bar{u}	\bar{d}	\bar{s}
carga (<i>Q</i>)	+ 2/3	-1/3	-1/3	-2/3	+1/3	+1/3
nº bariônico (<i>B</i>)	+ 1/3	+ 1/3	+ 1/3	-1/3	-1/3	-1/3
estranheza (<i>S</i>)	0	0	-1	0	0	+1
<i>isospin</i> (I_3)	+ 1/2	-1/2	0	-1/2	+ 1/2	0
hipercarga (<i>Y</i>)	+ 1/3	+1/3	-2/3	-1/3	-1/3	+ 2/3

decupleteo dos bárions				I	S
$\Delta^{++}(uuu)$	$\Delta^{+}(uud)$	$\Delta^{\circ}(udd)$	$\Delta^{-}(ddd)$	$3/2$	0
$\Sigma^{*+}(uus)$	$\Sigma^{*\circ}(uds)$	$\Sigma^{*-}(dds)$		1	-1
$\Xi^{*\circ}(uss)$	$\Xi^{*-}(dss)$			$1/2$	-2
$\Omega^{-}(sss)$				0	-3

octeto dos bárions			I	S
$p(uud)$	$n(udd)$		$1/2$	0
$\Sigma^{+}(uus)$	$\Sigma^{\circ}(uds)$	$\Sigma^{-}(dds)$	1	-1
$\Xi^{\circ}(uss)$	$\Xi^{-}(dss)$		$1/2$	-2
$\Delta^{-}(uds)$			0	-3

noneto dos mésons			I	S
$K^{+}(u\bar{s})$	$K^{\circ}(d\bar{s})$		$1/2$	$+1$
$\pi^{+}(u\bar{d})$	$\pi^{\circ}(u\bar{u}, d\bar{d})$	$\pi^{-}(\bar{u}d)$	1	0
$\bar{K}^{\circ}(\bar{d}s)$	$K^{-}(\bar{d}s)$		$1/2$	-1
$\eta(u\bar{u}, d\bar{d}, s\bar{s})$			0	0
$\eta'(u\bar{u}, d\bar{d}, s\bar{s})$			0	0

Momento magnético do próton (uud) e do nêutron (udd)

$$\vec{\mu} = \left(\frac{q}{2m} \right) \vec{s}$$

$u = s_1, m_1\rangle$	$u = s_2, m_2\rangle$		$ J_{uu}, m_{uu}\rangle$	μ
$ 1/2, +1/2\rangle_1$	$ 1/2, +1/2\rangle_2$	compondo os autoestados →	$ 1, +1\rangle$	$2\mu_u$
$ 1/2, -1/2\rangle_1$	$ 1/2, -1/2\rangle_2$		$ 1, 0\rangle$	0
			$ 1, -1\rangle$	$-2\mu_u$

compondo os estados de spin $J_{uu} = 1$ com os auto estados de spin $s_d = 1/2$ do quark d, os auto estados correspondentes ao spin $J_p = 1/2$ do próton serão dados por

$$\begin{cases} |J_p = 1/2, m_{J_p} = +1/2\rangle = \sqrt{\frac{2}{3}} |1, 1\rangle |1/2, -1/2\rangle - \sqrt{\frac{1}{3}} |1, 0\rangle |1/2, +1/2\rangle \\ |J_p = 1/2, m_{J_p} = -1/2\rangle = \sqrt{\frac{1}{3}} |1, 0\rangle |1/2, -1/2\rangle - \sqrt{\frac{2}{3}} |1, -1\rangle |1/2, +1/2\rangle \end{cases}$$

$$\mu_p = \frac{2}{3}(2\mu_u - \mu_d) + \frac{1}{3}\mu_d = \frac{1}{3}(4\mu_u - \mu_d) \quad (m_{Jp} = \frac{1}{2})$$

$$\mu_n = \frac{2}{3}(2\mu_d - \mu_u) + \frac{1}{3}\mu_u = \frac{1}{3}(4\mu_d - \mu_u) \quad (m_{Jn} = \frac{1}{2})$$

$$\begin{array}{l} (m_{Jn} = \frac{1}{2}) \\ q_u = -2q_d \end{array} \quad \rightarrow \quad \left(\frac{\mu_n}{\mu_p} \right)_{\text{teor}} = -\frac{2}{3} \simeq -0,67$$

$$\left(\frac{\mu_n}{\mu_p} \right)_{\text{exp}} = -0,68$$

Grupo SU(3) de cor

- bárion mais leve do decuplete em um autoestado de $m_j = 3/2$
- simétrico em sabor e troca de dois quarks

$$\Delta^{++} \left(m_J = +\frac{3}{2} \right) = (uuu)(\uparrow\uparrow\uparrow) = u^\uparrow u^\uparrow u^\uparrow \quad u^\uparrow = u \left(m_j = +\frac{1}{2} \right)$$

- novo grau de liberdade para os quarks (Greenberg - 1964)
- interações fortes não distinguem sabores de quarks, resultam de uma nova propriedade dos quarks, a cor (Han e Nambu - 1965)

- decuplete dos bárions corresponderia aos seguintes 10 estados simétricos com relação ao sabor

$$\left. \begin{aligned}
 \Delta^{++} &= uuu \\
 \Delta^{+} &= \frac{1}{\sqrt{3}} (uud + udu + duu) \\
 \Delta^{0} &= \frac{1}{\sqrt{3}} (udd + dud + ddu) \\
 \Delta^{-} &= ddd
 \end{aligned} \right\} \quad I = \frac{3}{2} \quad S = 0 \quad Y = +1$$

$$\left. \begin{aligned}
 \Sigma^{*+} &= \frac{1}{\sqrt{3}} (uus + usu + suu) \\
 \Sigma^{*0} &= \frac{1}{\sqrt{6}} (uds + usd + dus + dsu + sud + sdu) \\
 \Sigma^{*-} &= \frac{1}{\sqrt{3}} (dds + dsd + sdd)
 \end{aligned} \right\} \quad I = 1 \quad S = -1 \quad Y = 0$$

$$\left. \begin{aligned}
 \Xi^{*0} &= \frac{1}{\sqrt{3}} (uss + sus + ssu) \\
 \Xi^{*-} &= \frac{1}{\sqrt{3}} (dss + sds + ssd)
 \end{aligned} \right\} \quad I = \frac{1}{2} \quad S = -2 \quad Y = -1$$

$$\left. \begin{aligned}
 \Omega^{-} &= sss
 \end{aligned} \right\} \quad I = 0 \quad S = -3 \quad Y = -2$$

Próton - autoestado de spin $|m=+\frac{1}{2}\rangle$

produto de estados antissimétricos de spin e sabor

$$(ud - du) (\uparrow\downarrow - \downarrow\uparrow) = u^\uparrow d^\downarrow - u^\downarrow d^\uparrow - d^\uparrow u^\downarrow + d^\downarrow u^\uparrow$$

incorporando um quark u ($m=+\frac{1}{2}$) \rightarrow simétrica
(primeiro quark u com o quark d)

$$(u^\uparrow d^\downarrow - u^\downarrow d^\uparrow - d^\uparrow u^\downarrow + d^\downarrow u^\uparrow) u^\uparrow = (udu - duu) (\uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow)$$

totalmente simétrica (sabor e spin)

$$(udu - duu) (\uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow) + (uud - duu) (\uparrow\uparrow\downarrow - \downarrow\uparrow\uparrow) + (uud - udu) (\uparrow\uparrow\downarrow - \uparrow\downarrow\uparrow)$$

estado normalizado $|m=+\frac{1}{2}\rangle$

$$p(\uparrow) = \frac{1}{\sqrt{18}} (2u^\uparrow u^\uparrow d^\downarrow + 2d^\downarrow u^\downarrow u^\uparrow + 2u^\uparrow d^\downarrow u^\uparrow + \\ - u^\uparrow u^\downarrow d^\uparrow - u^\uparrow d^\uparrow u^\downarrow - d^\uparrow u^\uparrow u^\downarrow + \\ - u^\downarrow u^\uparrow d^\uparrow - u^\downarrow d^\uparrow u^\uparrow - d^\uparrow u^\downarrow u^\uparrow)$$

Espalhamento $e^+ e^-$

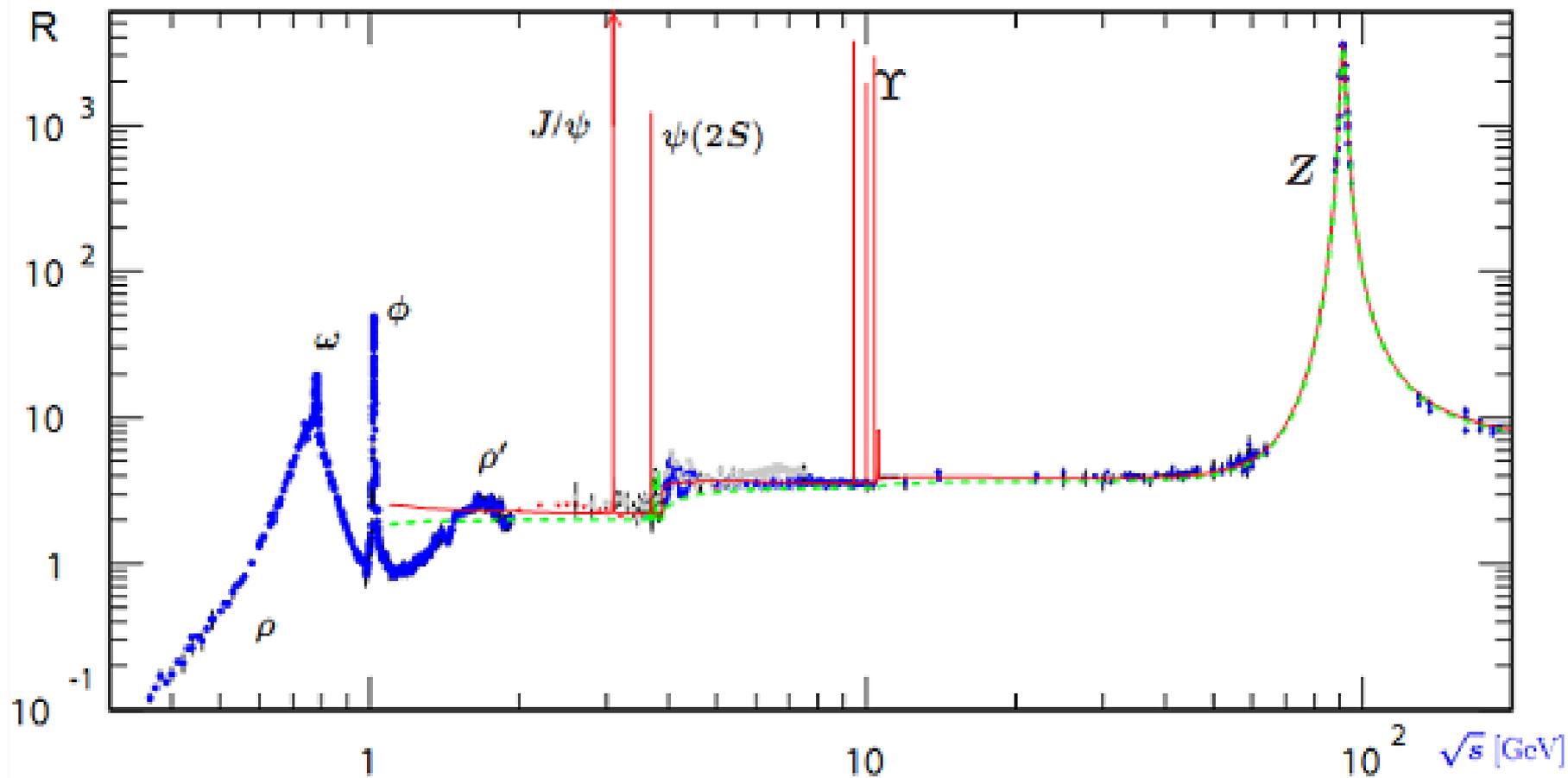
$$\sigma(e^-e^+ \rightarrow \mu^+\mu^-) = \frac{4\pi\alpha^2}{3s}$$

$$\sigma(e^-e^+ \rightarrow q\bar{q}) = \frac{4\pi\alpha^2}{3s} e_q^2$$

$$\frac{\sigma(e^-e^+ \rightarrow q\bar{q})}{\sigma(e^-e^+ \rightarrow \mu^+\mu^-)} = e_q^2$$

$$R = \frac{\sigma(e^-e^+ \rightarrow \text{hádrons})}{\sigma(e^-e^+ \rightarrow \mu^+\mu^-)} = \sum_{q, \text{ cores}} e_q^2 = 3 \sum_q e_q^2$$

depende do número de quarks



PDG - 2012

Energia	Sabores	R
$\sqrt{s} > 2m_s \sim 1 \text{ GeV}$	u, d, s	$3 \left(\frac{4}{9} + \frac{1}{9} + \frac{1}{9} \right) = 2$
$\sqrt{s} > 2m_c \sim 4 \text{ GeV}$	u, d, s, c	$3 \left(\frac{4}{9} + \frac{1}{9} + \frac{1}{9} + \frac{4}{9} \right) = 3\frac{1}{3}$
$\sqrt{s} > 2m_b \sim 10 \text{ GeV}$	u, d, s, c, b	$3 \left(\frac{4}{9} + \frac{1}{9} + \frac{1}{9} + \frac{4}{9} + \frac{1}{9} \right) = 3\frac{2}{3}$
$\sqrt{s} > 2m_t \sim 350 \text{ GeV}$	u, d, s, c, b, t	$3 \left(\frac{4}{9} + \frac{1}{9} + \frac{1}{9} + \frac{4}{9} + \frac{1}{9} + \frac{4}{9} \right) = 5$

cargas de cor e cargas fortes

- quarks: red (r), green (g) e blue (b)
- antiquarks: \bar{r} \bar{g} \bar{b}
- hádrons não têm a propriedade de cor
- singletos associados ao grupo $SU(3)_c$

- bárions (antissimétrico)

$$q_1 q_2 q_3 = \frac{1}{\sqrt{6}} (r_1 b_2 g_3 - b_1 r_2 g_3 + b_1 g_2 r_3 - g_1 b_2 r_3 + g_1 r_2 b_3 - r_1 g_2 b_3)$$

- mésons (simétrico)

$$q_1 \bar{q}_2 = \frac{1}{\sqrt{3}} (r_1 \bar{r}_2 + g_1 \bar{g}_2 + b_1 \bar{b}_2)$$

- com a descoberta novas ressonâncias e argumentos teóricos associados aos decaimentos por interações fracas, novos quarks foram introduzidos, os chamados sabores pesados, como o quark charm (c) e os quarks bottom (b) e top (t), com massas da ordem de $m_c \simeq 1\text{GeV}$, $m_b \simeq 5\text{GeV}$ e $m_t \simeq 172\text{ GeV}$
- com esses novos quarks, em analogia com a estranheza (S), atribuída ao quark s, foram introduzidos e atribuídos os números quânticos aditivos ao quark charm ($c = +1$), ao quark bottom ($b = -1$) e ao quark top ($t = +1$)
- esses números se conservam nas interações fortes e eletromagnéticas, mas não nas interações fracas, as quais permitem a mudança de sabor

$$Y = B + S + c + b + t \text{ (hipercarga de um quark)}$$

- quarks interagem fortemente devido a cor – QCD (Cromodinâmica Quântica)
- grupo $SU(3)_c$

$$U = \exp \left\{ i g_s \alpha_k \frac{\lambda_k}{2} \right\}$$

- 8 geradores: $\{\lambda_k \mid k = 1, 2, \dots, 8\}$ (matrizes de Gell-Mann)
- 8 parâmetros : $\{\alpha_k \mid k = 1, 2, \dots, 8\}$ (cargas fortes)
- g_s : constante de acoplamento forte

- reações fortes resultam da interação de um octeto de cor – glúons, resultante da composição cor-anticor ($3 \otimes \bar{3} = 8 \oplus 1$) com tripleto de cor – quarks

$$\frac{1}{\sqrt{2}} (r \bar{g} + g \bar{r})$$

$$\frac{-i}{\sqrt{2}} (r \bar{g} - g \bar{r})$$

$$\frac{1}{\sqrt{2}} (r \bar{r} - g \bar{g})$$

$$\frac{1}{\sqrt{2}} (r \bar{b} + b \bar{r})$$

$$\frac{-i}{\sqrt{2}} (r \bar{b} - b \bar{r})$$

$$\frac{1}{\sqrt{2}} (g \bar{b} + b \bar{g})$$

$$\frac{-i}{\sqrt{2}} (g \bar{b} - b \bar{g})$$

$$\frac{1}{\sqrt{6}} (r \bar{r} + g \bar{g} - 2b \bar{b})$$

Clebsch-Gordon

Note: A square-root sign is to be understood over every coefficient, e.g., for $-8/15$ read $-\sqrt{8/15}$.

Notation:

j_1	j_2	\dots
M_1	M_2	\dots
m_1	m_2	Coefficients
m_1	m_2	
\vdots	\vdots	
\vdots	\vdots	

$$1/2 \times 1/2$$

		1		
	+1/2+1/2	+1	1	0
		1	0	0
+1/2	-1/2	1/2	1/2	1
-1/2	+1/2	1/2	-1/2	-1
		-1/2	-1/2	1

$$Y_1^0 = \sqrt{\frac{3}{4\pi}} \cos \theta$$

$$Y_1^1 = -\sqrt{\frac{3}{8\pi}} \sin \theta e^{i\phi}$$

$$Y_2^0 = \sqrt{\frac{5}{4\pi}} \left(\frac{3}{2} \cos^2 \theta - \frac{1}{2} \right)$$

$$Y_2^1 = -\sqrt{\frac{15}{8\pi}} \sin \theta \cos \theta e^{i\phi}$$

$$Y_2^2 = \frac{1}{4} \sqrt{\frac{15}{2\pi}} \sin^2 \theta e^{2i\phi}$$

$$2 \times 1/2$$

		5/2			
	+5/2	5/2	3/2		
		1	+3/2+3/2		
+2	-1/2	1/5	4/5	5/2	3/2
+1	+1/2	4/5	-1/5	+1/2	+1/2

$$3/2 \times 1/2$$

		2			
	+2	2	1		
		1	+1	+1	
+3/2	+1/2	1/4	3/4	2	1
+1/2	+1/2	3/4	-1/4	0	0

$$1 \times 1/2$$

		3/2			
	+3/2	3/2	1/2		
		1	+1/2	-1/2	
+1	-1/2	1/3	2/3	3/2	1/2
0	+1/2	2/3	-1/3	-1/2	-1/2

$$2 \times 1$$

		3				
	+3	3	2			
		1	+2	+2		
+2	0	1/3	2/3	3	2	1
+1	+1	2/3	-1/3	+1	+1	+1

$$3/2 \times 1$$

		5/2				
	+5/2	5/2	3/2			
		1	+3/2	+3/2		
+3/2	0	2/5	3/5	5/2	3/2	1/2
+1/2	+1	3/5	-2/5	+1/2	+1/2	+1/2

		2	1		
+1/2	-1/2	1/2	1/2	2	1
-1/2	+1/2	1/2	-1/2	-1	-1
-1/2	-1/2	3/4	1/4	2	
-3/2	+1/2	1/4	-3/4	-2	
		-3/2	-1/2	1	

$$1 \times 1$$

		2				
	+2	2	1			
		1	+1	+1		
+1	0	1/2	1/2	2	1	0
0	+1	1/2	-1/2	0	0	0

		3	2	1			
+1	-1	1/5	1/2	3/10	3	2	1
0	0	3/5	0	-2/5	3	2	1
-1	+1	1/5	-1/2	3/10	-1	-1	-1

		5/2	3/2	1/2			
+1/2	-1	3/10	8/15	1/6	5/2	3/2	1/2
-1/2	0	3/5	-1/15	-1/3	5/2	3/2	
-3/2	+1	1/10	-2/5	1/2	-3/2	-3/2	
		-1/2	-1/2	-1/2			

		2	1			
+1	-1	1/6	1/2	1/3	2	1
0	0	2/3	0	-1/3	2	1
-1	+1	1/6	-1/2	1/3	-1	-1

		3	2			
0	-1	2/5	1/2	1/10	3	2
-1	0	8/15	-1/6	-3/10	3	2
-2	+1	1/15	-1/3	3/5	-2	-2

		5/2		
-1/2	-1	3/5	2/5	5/2
-3/2	0	2/5	-3/5	-5/2
		-3/2	-1	1

$$Y_\ell^{-m} = (-1)^m Y_\ell^{m*}$$

$$d_{m,0}^\ell = \sqrt{\frac{4\pi}{2\ell+1}} Y_\ell^m e^{-im\phi}$$

$$\langle j_1 j_2 m_1 m_2 | j_1 j_2 J M \rangle = (-1)^{J-j_1-j_2} \langle j_2 j_1 m_2 m_1 | j_2 j_1 J M \rangle$$

Clebsch-Gordon

$$d_{m',m}^j = (-1)^{m-m'} d_{m,m'}^j = d_{-m,-m'}^j$$

3/2 x 3/2

	3		
	+3	3	2
+3/2 +3/2	1	+2	+2

$$d_{0,0}^1 = \cos \theta$$

$$d_{1/2,1/2}^{1/2} = \cos \frac{\theta}{2}$$

$$d_{1,1}^1 = \frac{1 + \cos \theta}{2}$$

$$d_{1,0}^1 = -\frac{\sin \theta}{\sqrt{2}}$$

$$d_{1,-1}^1 = \frac{1 - \cos \theta}{2}$$

2 x 3/2

	7/2			
	+7/2	7/2	5/2	
+2+3/2	1	+5/2+5/2		

		3	2	1
	+3/2+1/2	1/2	1/2	
+1/2+3/2		1/2-1/2		

		3	2	1	0
	+3/2-1/2	1/5	1/2	3/10	
+1/2+1/2		3/5	0	-2/5	
-1/2+3/2		1/5	-1/2	3/10	

		3	2	1	0
	+3/2-3/2	1/20	1/4	9/20	1/4
+1/2-1/2		9/20	1/4	-1/20	-1/4
-1/2+1/2		9/20	-1/4	-1/20	1/4
-3/2+3/2		1/20	-1/4	9/20	-1/4

2 x 2

	4		
	+4	4	3
+2+2	1	+3	+3

		4	3	2
	+2+1	1/2	1/2	
+1+2		1/2-1/2		

		7/2	5/2	3/2	1/2
	+2-3/2	1/35	6/35	2/5	2/5
+1-1/2		12/35	5/14	0	-3/10
0+1/2		18/35	-3/35	-1/5	1/5
-1+3/2		4/35	-27/70	2/5	-1/10

		7/2	5/2	3/2	1/2
	+1-3/2	4/35	27/70	2/5	1/10
0-1/2		18/35	3/35	-1/5	-1/5
-1+1/2		12/35	-5/14	0	3/10
-2+3/2		1/35	-6/35	2/5	-2/5

		3	2	1
	+1/2-3/2	1/5	1/2	3/10
-1/2-1/2		3/5	0	-2/5
-3/2+1/2		1/5	-1/2	3/10

		3	2
	+1/2-3/2	1/5	1/2
-1/2-1/2		3/5	0
-3/2+1/2		1/5	-1/2

		4	3	2	1
	+2 0	3/14	1/2	2/7	
+1+1		4/7	0	-3/7	
0+2		3/14	-1/2	2/7	

		4	3	2	1
	+2 -1	1/14	3/10	3/7	1/5
+1 0		3/7	1/5	-1/14	-3/10
0+1		3/7	-1/5	-1/14	3/10
-1+2		1/14	-3/10	3/7	-1/5

		4	3	2	1	0
	+2 -2	1/70	1/10	2/7	2/5	1/5
+1 -1		8/35	2/5	1/14	-1/10	-1/5
0 0		18/35	0	-2/7	0	1/5
-1+1		8/35	-2/5	1/14	1/10	-1/5
-2+2		1/70	-1/10	2/7	-2/5	1/5

		7/2	5/2	3/2
	0 -3/2	2/7	18/35	1/5
-1 -1/2		4/7	-1/35	-2/5
-2 +1/2		1/7	-16/35	2/5

		1/2	1/2	3
	-1/2 -3/2	1/2	1/2	3
-3/2 -1/2		1/2	-1/2	-3
-3/2 -3/2		1/2	-1/2	1

$$d_{3/2,3/2}^{3/2} = \frac{1 + \cos \theta}{2} \cos \frac{\theta}{2}$$

$$d_{3/2,1/2}^{3/2} = -\sqrt{3} \frac{1 + \cos \theta}{2} \sin \frac{\theta}{2}$$

$$d_{3/2,-1/2}^{3/2} = \sqrt{3} \frac{1 - \cos \theta}{2} \cos \frac{\theta}{2}$$

$$d_{3/2,-3/2}^{3/2} = -\frac{1 - \cos \theta}{2} \sin \frac{\theta}{2}$$

$$d_{1/2,1/2}^{3/2} = \frac{3 \cos \theta - 1}{2} \cos \frac{\theta}{2}$$

$$d_{2,2}^2 = \left(\frac{1 + \cos \theta}{2} \right)^2$$

$$d_{2,1}^2 = -\frac{1 + \cos \theta}{2} \sin \theta$$

$$d_{2,0}^2 = \frac{\sqrt{6}}{4} \sin^2 \theta$$

$$d_{2,-1}^2 = -\frac{1 - \cos \theta}{2} \sin \theta$$

$$d_{1,1}^2 = \frac{1 + \cos \theta}{2} (2 \cos \theta - 1)$$

$$d_{1,0}^2 = -\sqrt{\frac{3}{2}} \sin \theta \cos \theta$$

		4	3	2	1
	+1 -2	1/14	3/10	3/7	1/5
0 -1		3/7	1/5	-1/14	-3/10
-1 0		3/7	-1/5	-1/14	3/10
-2 +1		1/14	-3/10	3/7	-1/5

		4	3	2
	-1-3/2	4/7	3/7	7/2
-2-1/2		3/7	-4/7	-7/2

		4	3
	-2-3/2	4	3

		4	3
	0 -2	3/14	1/2
-1 -1		4/7	0
-2 0		3/14	-1/2

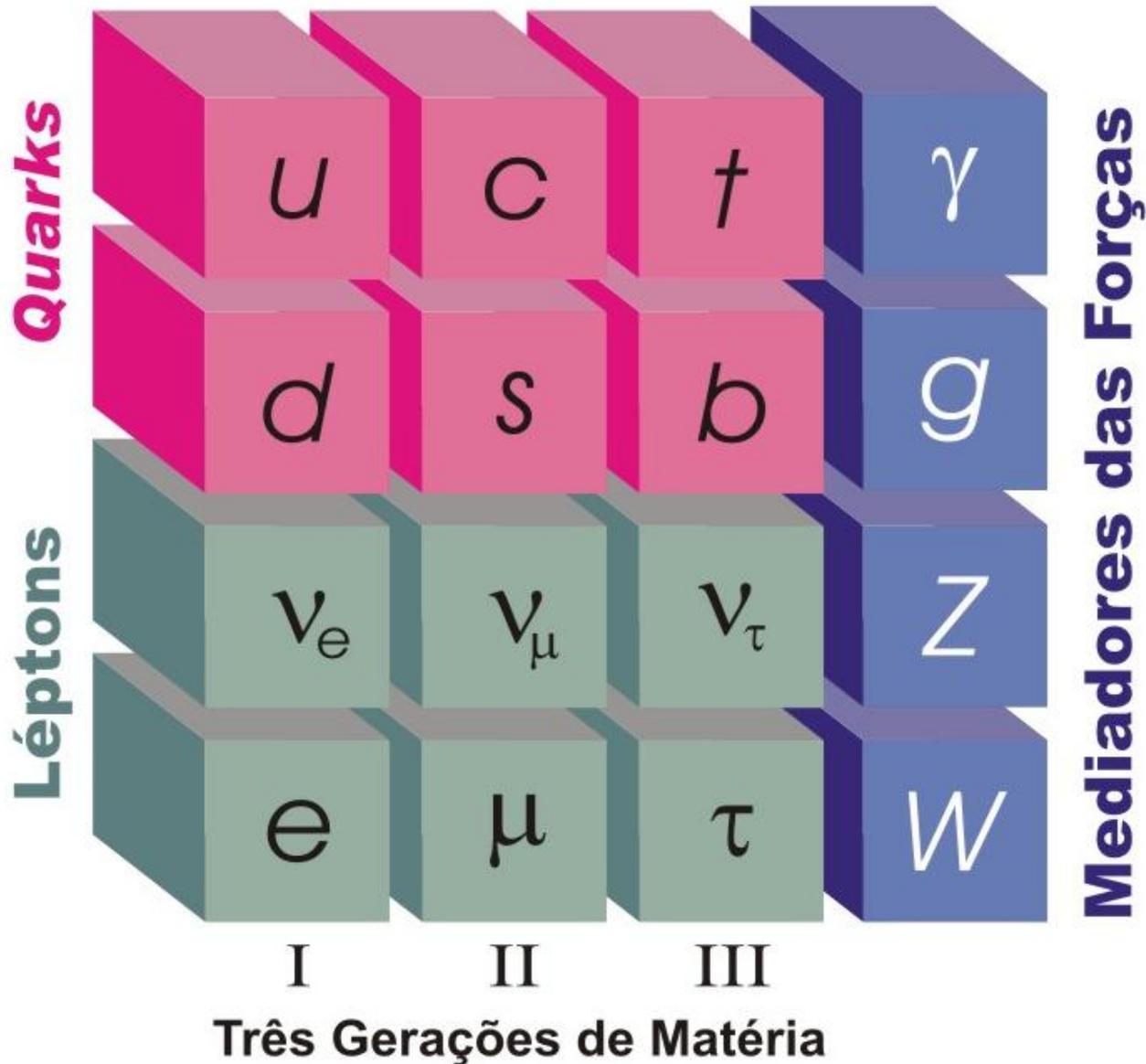
		4	3
	-1 -2	1/2	1/2
-2 -1		1/2	-1/2

		4
	-2 -2	4

Quarks

- Quarks como sendo as partículas envolvidas diretamente nas interações fortes foram postulados por Murray Gell-Mann e G. Zweig, nos anos de 1960, segundo argumentos de simetria, como os elementos constituintes dos hádrons.
- Do ponto de vista dinâmico, os quarks como constituintes dos hádrons começaram a emergir dos trabalhos experimentais de R. Hofstadter, nos anos de 1950, no centro de aceleradores de elétrons da Universidade de Stanford, no qual estabeleceu a subestrutura do próton.
- Finalmente, foram estabelecidos ao final dos anos de 1960, com os experimentos de espalhamento profundamente inelástico de elétrons por prótons, também em Stanford (SLAC), liderados por J.I. Friedman (MIT), H.W. Kendall (MIT) e R.E. Taylor do SLAC, e com os trabalhos teóricos (modelo a partons) de J. D. Bjorken e R. Feynman.

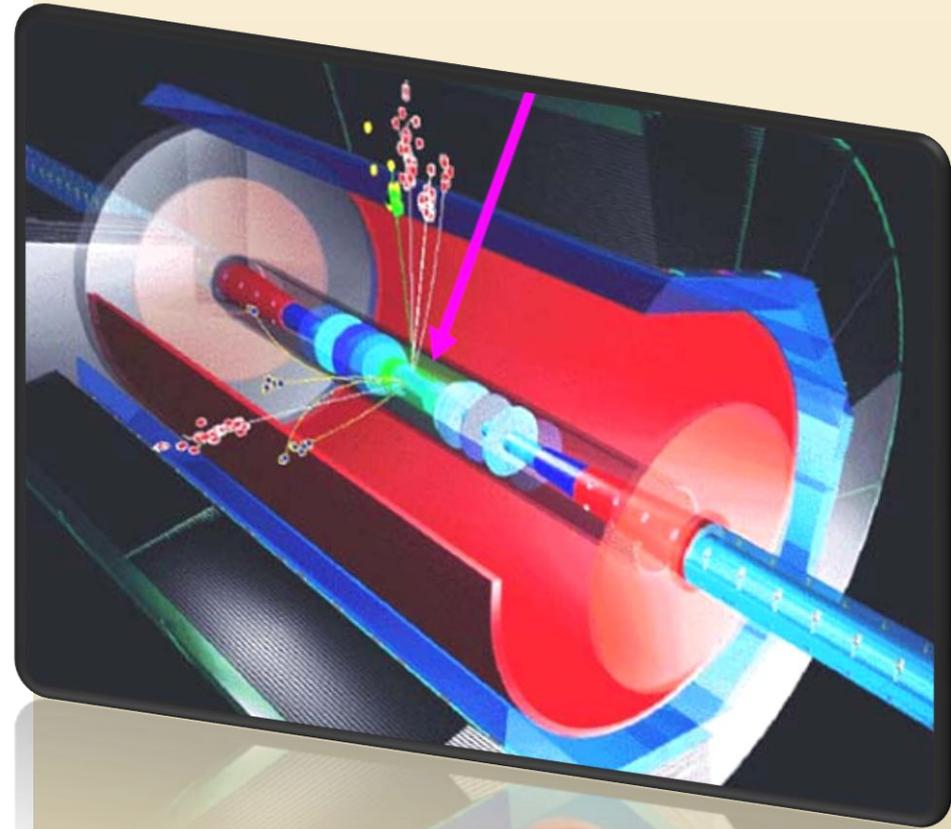
Quarks e léptons



Experimentos	Hipóteses e teorias	Aceleradores e detectores
<p>pósitron (Anderson, Caltech - 1932)</p> <p>múon (Neddermeyer & Anderson, Caltech - 1936)</p> <p>píon (Powell <i>et al</i>, Bristol - 1947)</p> <p>káon (Rochester & Butter, Manchester - 1947)</p> <p>$\bar{\mu}_e$ anômalo (Kusch & Foley, Columbia - 1947)</p> <p>ressonância (Δ) (Fermi <i>et al</i>, Chicago - 1952)</p> <p>antipróton (Chamberlain <i>et al</i>, Berkeley - 1955)</p> <p>raio do próton (Hofstadter <i>et al</i>, SLAC - 1956)</p> <p>violação da paridade (Wu <i>et al</i>, NBS - 1957)</p> <p>helicidade do neutrino (Goldhaber <i>et al</i>, BNL - 1957)</p> <p>ressonância (ρ^0) (Erwin <i>et al</i>, BNL - 1961)</p> <p>ressonâncias (Alvarez <i>et al</i>, Berkeley - 1961)</p> <p>neutrino do múon (ν_μ) (Lederman <i>et al</i>, BNL - 1962)</p> <p>(Ω^-) (Samios <i>et al</i>, BNL - 1964)</p> <p>CP violation (Cronin <i>et al</i>, BNL - 1964)</p> <p>deep inelastic (Friedman <i>et al</i>, SLAC - 1969)</p> <p>WNC (Lagarrigue <i>et al</i> - Gargamelle, CERN - 1973)</p> <p>charm (c) - ψ (Richter <i>et al</i>, SLAC - 1974)</p> <p>J (Ting <i>et al</i>, BNL - 1974)</p> <p>τ (Perl <i>et al</i>), jets (Hanson <i>et al</i>) - (SLAC - 1975)</p> <p>bottom (b) (Lederman <i>et al</i>, Fermilab - 1977)</p> <p>gluon jets (TASSO, DESY - 1979)</p> <p>W^\pm, Z (Rubbia <i>et al</i> - UA1, CERN - 1983)</p> <p>top (t) (CDF/DØ, Fermilab - 1995)</p> <p>neutrino do tau (ν_τ) (DONUT, Fermilab - 2000)</p>	<p>equação de Dirac (1928)</p> <p>antipartícula (Dirac - 1930) e neutrino (Pauli - 1930)</p> <p>isospin (Heisenberg - 1932)</p> <p>beta decay (Fermi - 1934)</p> <p>méson π (Yukawa - 1935)</p> <p>QED (Feynman, Tomonaga, Schwinger - 1947)</p> <p>estranheza (Gell-Mann, Nishijima - 1953)</p> <p>violação da paridade (Lee, Yang - 1956)</p> <p>V-A (Feynman, Gell-Mann - 1958)</p> <p>mixing flavor (Cabibbo - 1963)</p> <p>quarks (Gell-Mann, Zweig - 1964) e Higgs (1964)</p> <p>$SU_c(3)$ (cor) (Greenberg, Han, Nambu - 1964-65)</p> <p>EW (Glashow, Salam, Weinberg - 1967)</p> <p>charm (GIM - 1970)</p> <p>renormalizabilidade (Veltman, 't Hooft - 1972)</p> <p>bottom - CKM (Kobayashi, Maskawa - 1973)</p> <p>QCD (Callan, Gross, Politzer, Wilczek, Fritzsche, Gell-Mann, Leutwyler <i>et al</i> - 1973)</p>	<p>Cíclotron (Berkeley) (80 keV - 1930)</p> <p>• câmara de bolhas (Glaser, Berkeley - 1952)</p> <p>Cosmotron (BNL) (3.3 GeV - 1953)</p> <p>Bevatron (Berkeley) (6.2 GeV - 1954)</p> <p>SLAC (e^- @ 180 MeV - 1955)</p> <p>• spark chamber (Conversi, CERN - 1955)</p> <p>PS (CERN) (p @ 28 GeV - 1959)</p> <p>AGS (BNL) (p @ 33 GeV - 1960)</p> <p>SLAC (e^- ou e^+ @ 50 GeV - 1966)</p> <p>• MWPC (Charpak <i>et al</i>, CERN - 1968)</p> <p>Fermilab (p @ 400 GeV - 1970)</p> <p>ISR (CERN) (pp @ 60 GeV - 1971)</p> <p>• drift chamber (Walenta <i>et al</i>, CERN - 1971)</p> <p>SPEAR (SLAC) (e^+e^- @ 3.7+3.7 GeV - 1972)</p> <p>PETRA (DESY) (e^+e^- @ 40 GeV - 1978)</p> <p>SPS (CERN) ($p\bar{p}$ @ 540-630 GeV - 1981)</p> <p>LEP I (CERN) (e^+e^- @ 91 GeV - 1989)</p> <p>TEVATRON I (Fermilab) ($p\bar{p}$ @ 1.8 TeV - 1992)</p> <p>LEP II (CERN) (e^+e^- @ 210 GeV - 1996)</p> <p>TEVATRON II (Fermilab) ($p\bar{p}$ @ 2 TeV - 2001)</p> <p>LHC (CERN) (pp @ 7 TeV - 2010)</p>

Experimentos em Física de Altas Energias

- As interações fundamentais da natureza se manifestam em colisões de partículas em altas energias.
- Os aceleradores de partículas proporcionam que essas interações ocorram, continuamente, em uma pequena região do espaço (vértice da colisão).
- A partir desses vértices outras partículas secundárias são criadas (eventos), e se afastam em todas as direções, em um amplo intervalo de energia.



Objetivos gerais

- Identificação de partículas (elétrons, múons, neutrinos, quarks, bósons mediadores, hádrons)
- Determinação de atributos intrínsecos (carga, massa, momento magnético, spin, tempo de vida, branching ratios)
- Medição de parâmetros associados aos fenômenos envolvidos (seção de choque, constantes de acoplamento)

Necessidades

- Determinação de posições, de trajetórias, de velocidades e tempos de voo
- Distribuições de grandezas geométricas (ângulos polar e azimutal, pseudo-rapidity) e cinemáticas (momentum, energia)

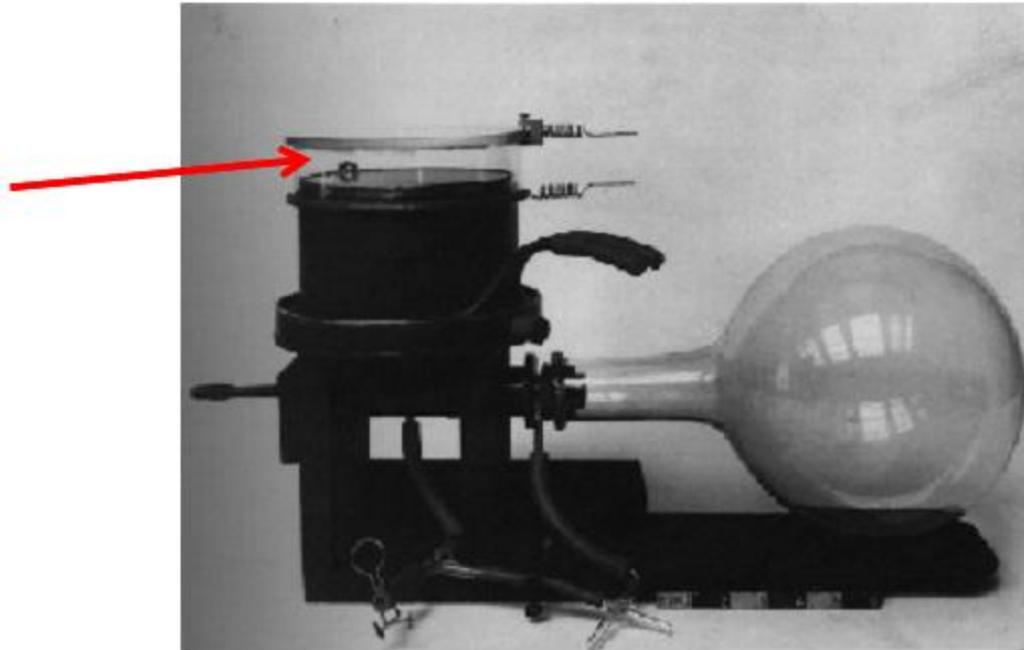
Soluções

- Sistemas complexos de detecção, organizados em subsistemas, os quais são compostos por vários tipos de detectores
- Experimentos com grande número de colaboradores (empreendimento coletivo)
- Grandes laboratórios internacionais (aceleradores)

Evolução

- ▶ Nos anos de 1960, os experimentos em Física de Partículas iniciam a transição das câmaras de bolhas para sistemas de detecção baseados em circuitos eletrônicos.
- ▶ Nos anos de 1970, com os experimentos em grandes aceleradores, e a necessidade de melhor identificação de partículas, os calorímetros e as grandes câmaras de fio tornam-se os componentes centrais dos experimentos em Altas Energias.
- ▶ A partir dos anos de 1990, câmaras de fio e cintiladores, desenvolvidos nos anos de 1950 na espectroscopia nuclear, são adaptados aos novos detectores, ou substituídos por semicondutores.

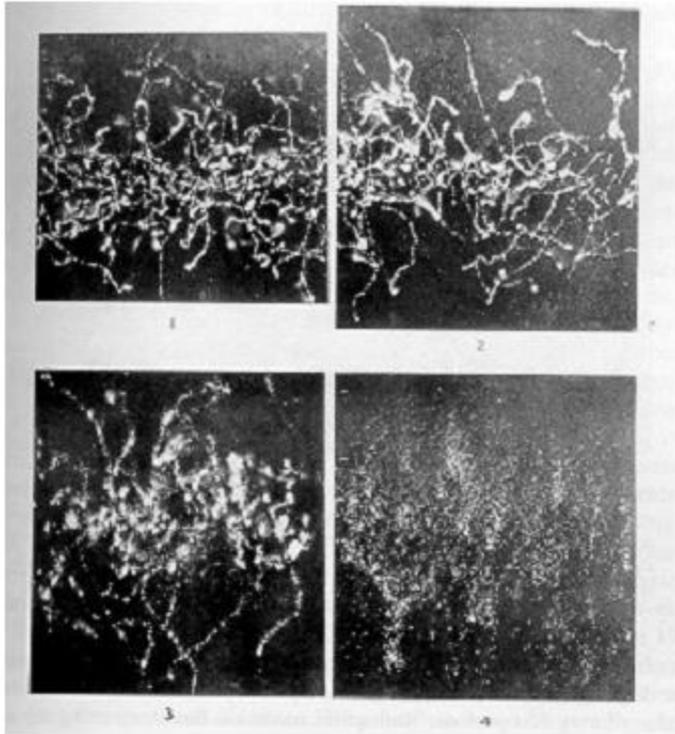
Cloud Chambers 1910-1950ies



Wilson Cloud Chamber 1911

The ions produced by a charged particle are leading to condensation in supersaturated water vapor. One finds small water droplets along the track that can be photographed.

Cloud Chamber 1910-1950ies



X-rays, Wilson 1912

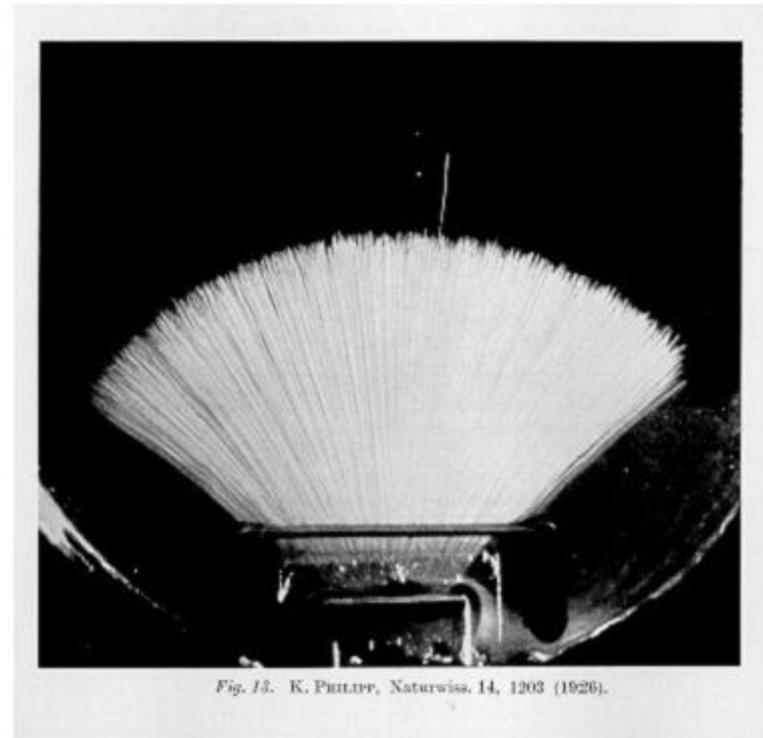
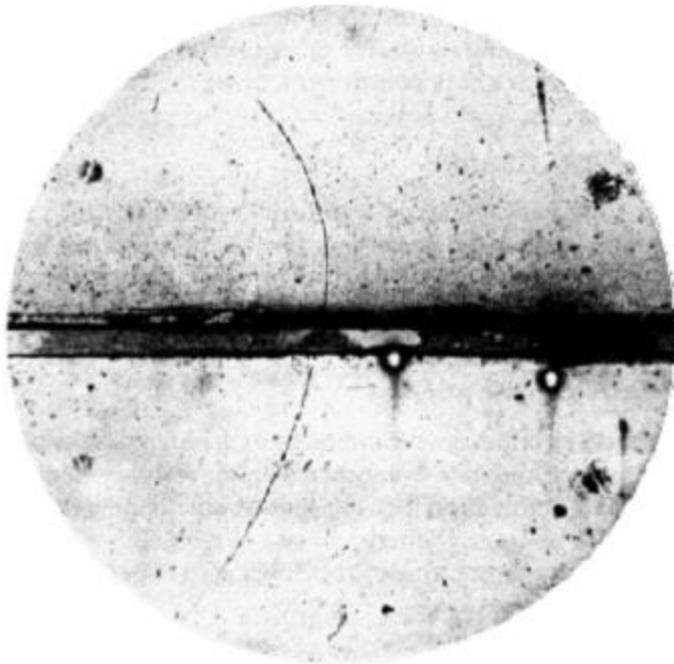


Fig. 13. K. PHILIPP, Naturwiss. 14, 1203 (1926).

Alphas, Philipp 1926

Cloud Chamber 1910-1950ies



Positron discovery,
Carl Andersen 1933

Magnetic field 15000 Gauss,
chamber diameter 15cm. A 63 MeV
positron passes through a 6mm lead plate,
leaving the plate with energy 23MeV.

The ionization of the particle, and its
behaviour in passing through the foil are
the same as those of an electron.

Cloud Chamber 1910-1950ies

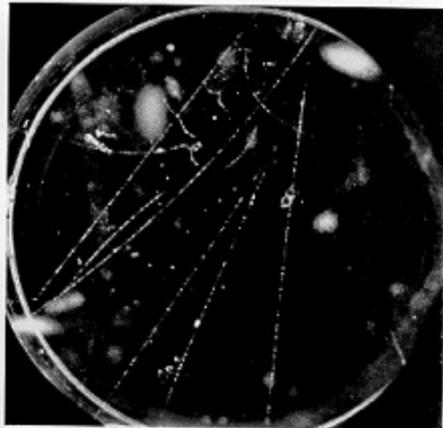


Plate 115

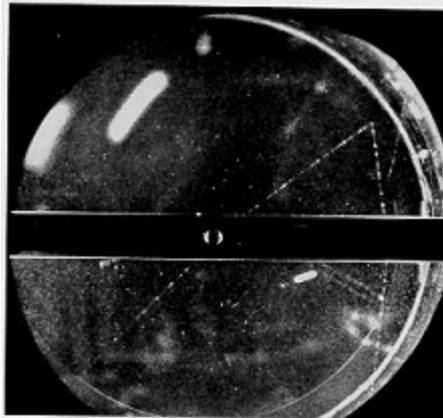


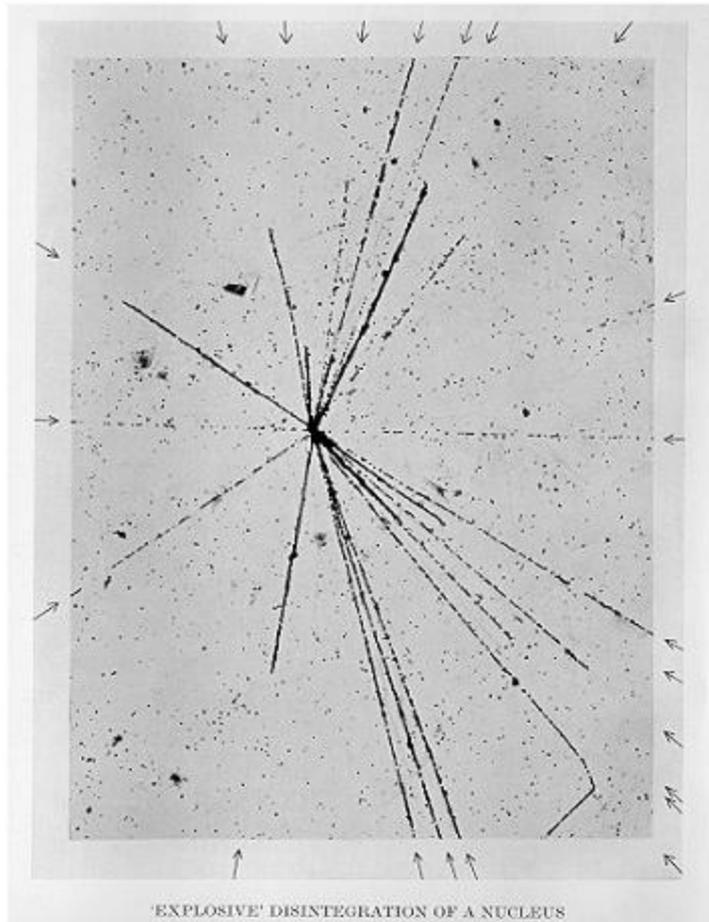
Plate 116

Rochester and Wilson

First observation of the “V0” particles in cosmic rays during the 1940ies. (now known as Kaon and Lambda)

‘ ... The V0 particle originates in a nuclear Interaction outside the chamber and decays after traversing about one third of the chamber. The momenta of the secondary particles are 1.6 ± 0.3 BeV/c and the angle between them is 12 degrees ... ‘

Nuclear Emulsion 1930ies to Present

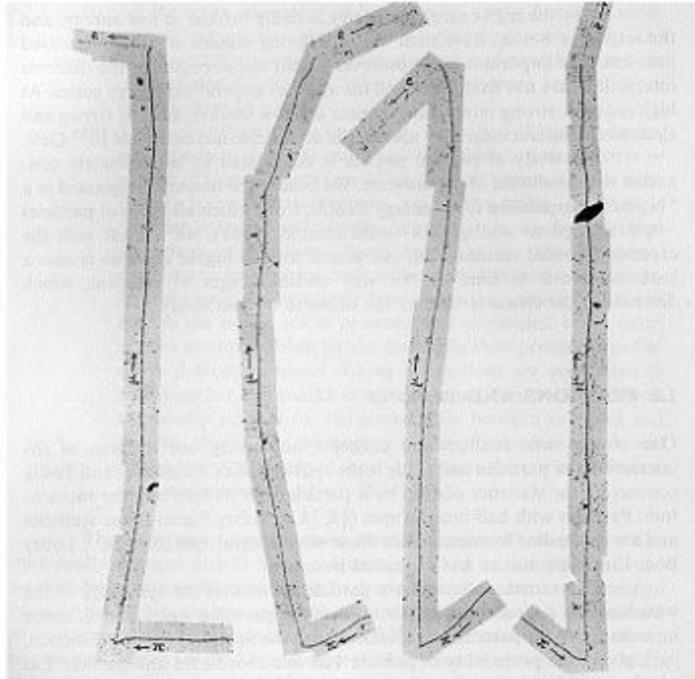


Film played an important role in the discovery of radioactivity but was first seen as a means of studying radioactivity rather than photographing individual particles.

Emulsions were exposed to cosmic rays at high altitude for a long time (months) and then analyzed under the microscope. In 1937, nuclear disintegrations from cosmic rays were observed in emulsions.

The high density of film compared to the cloud chamber 'gas' made it easier to see energy loss and disintegrations.

Nuclear Emulsion



Discovery of muon and pion

Discovery of the Pion:

The muon was discovered in the 1930ies and was first believed to be Yukawa's meson that mediates the strong force.

The long range of the muon was however causing contradictions with this hypothesis.

In 1947, Powell et. al. discovered the Pion in Nuclear emulsions exposed to cosmic rays, and they showed that it decays to a muon and an unseen partner.

The constant range of the decay muon indicated a two body decay of the pion.

Chamber 1950ies to early 1980ies

In the early 1950ies Donald Glaser tried to build on the cloud chamber analogy:

Instead of supersaturating a gas with a vapor one would superheat a liquid. A particle depositing energy along it's path would then make the liquid boil and form bubbles along the track.

In 1952 Glaser photographed first Bubble chamber tracks. Luis Alvarez was one of the main proponents of the bubble chamber.

The size of the chambers grew quickly

1954:	2.5" (6.4cm)
1954:	4" (10cm)
1956:	10" (25cm)
1959:	72" (183cm)
1963:	80" (203cm)
1973:	370cm

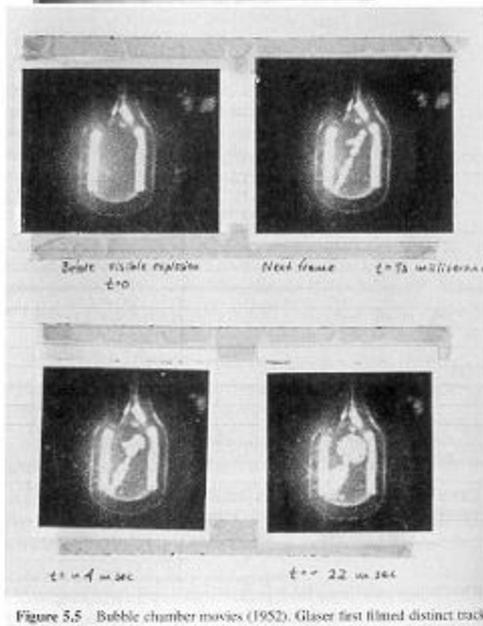
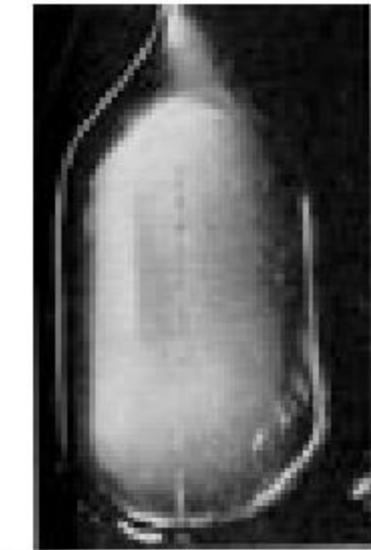
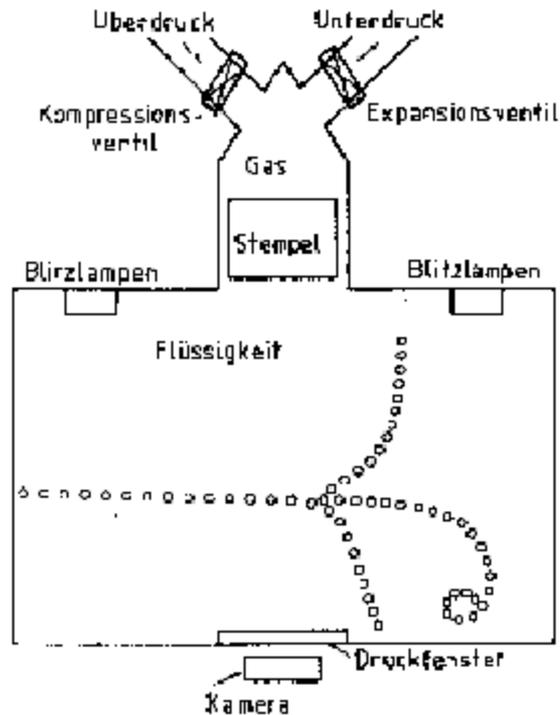
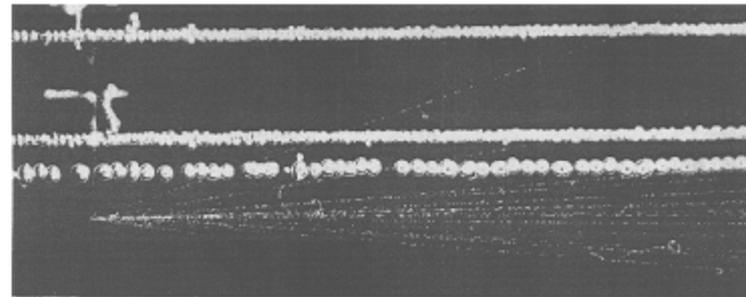


Figure 5.5 Bubble chamber movies (1952). Glaser first filmed distinct tracks

Bubble Chamber



'old bubbles'

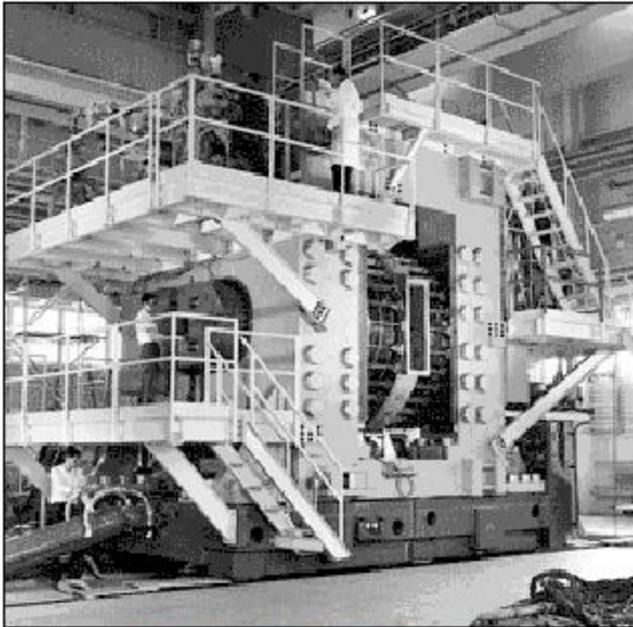


'new bubbles'

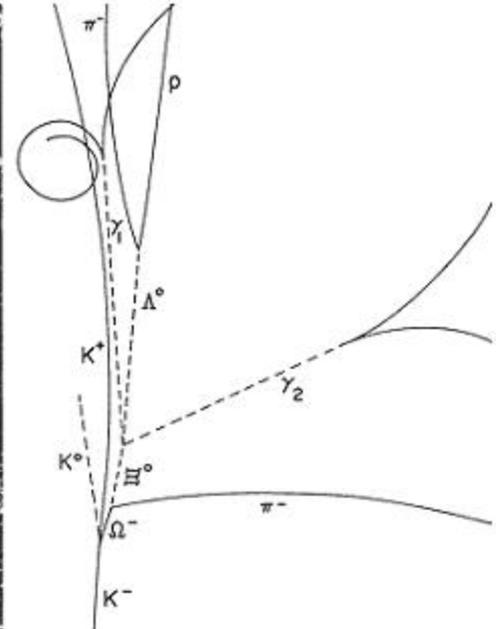
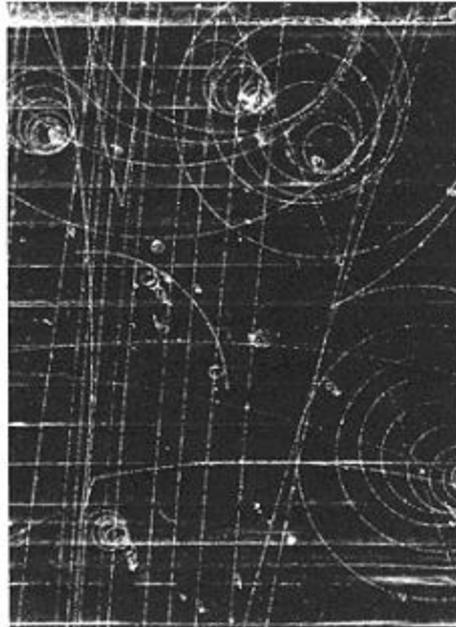
The Bubble Chamber can not be triggered, i.e. the bubble chamber had to be already in the superheated state when the particle was entering. Because in the 50ies particle physics moved to accelerators it was possible to synchronize the chamber compression with the arrival of the beam.

For data analysis one had to look through millions of pictures.

Bubble Chamber



The 80-inch Bubble Chamber



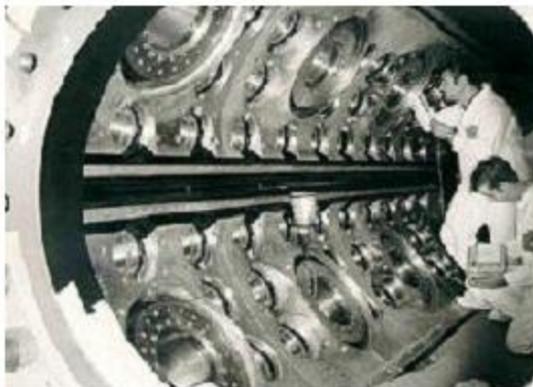
BNL, First Pictures 1963, 0.03s cycle

Discovery of the Δ^- in 1964

Bubble Chamber

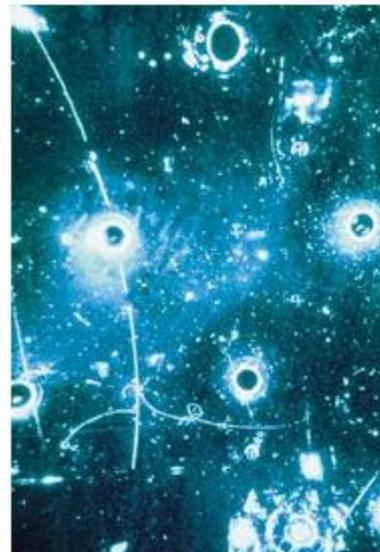


Can be seen outside the Microcosm Exhibition

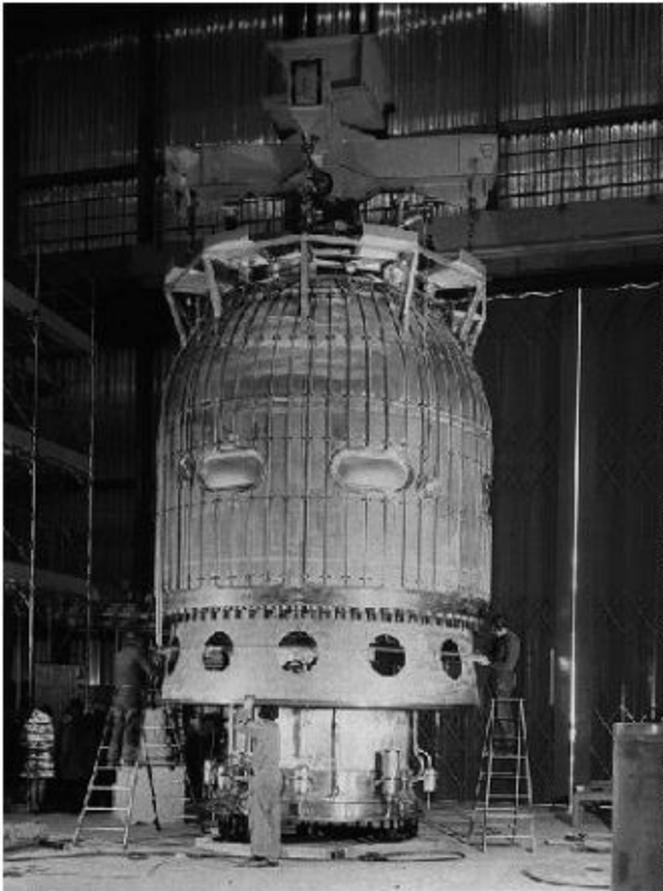


Gargamelle, a very large heavy-liquid (freon) chamber constructed at Ecole Polytechnique in Paris, came to CERN in 1970. It was 2 m in diameter, 4 m long and filled with Freon at 20 atm.

With a conventional magnet producing a field of almost 2 T, Gargamelle in 1973 was the tool that permitted the discovery of neutral currents.

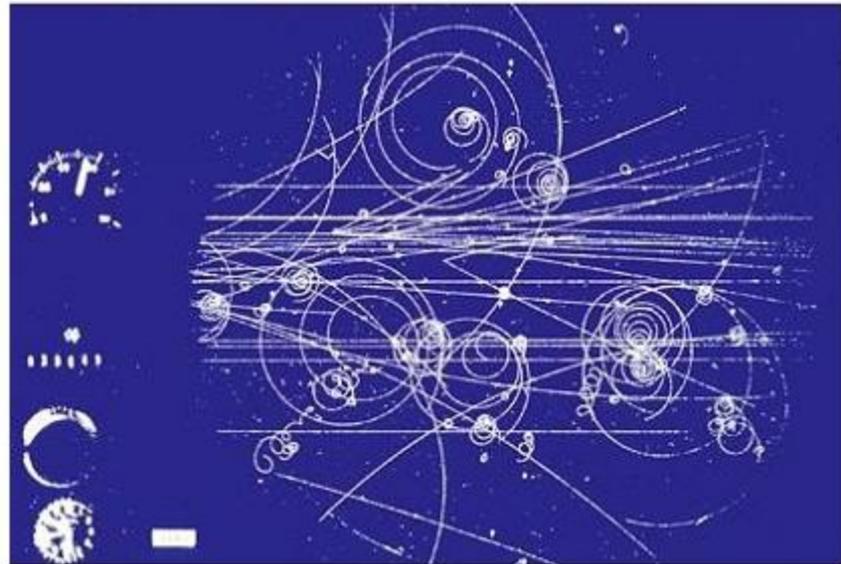


Bubble Chamber



3.7 meter hydrogen bubble chamber at CERN, equipped with the largest superconducting magnet in the world.

During its working life from 1973 to 1984, the "Big European Bubble Chamber" (BEBC) took over 6 million photographs.



Can be seen outside the Microcosm Exhibition

Bubble Chambers

The excellent position ($5\mu\text{m}$) resolution and the fact that target and detecting volume are the same (H chambers) makes the Bubble chamber almost unbeatable for reconstruction of complex decay modes.

The drawback of the bubble chamber is the low rate capability (a few tens/ second). E.g. LHC 10^9 collisions/s.

The fact that it cannot be triggered selectively means that every interaction must be photographed.

Analyzing the millions of images by 'operators' was a quite laborious task.

That's why electronics detectors took over in the 70ties.

Calorimetry

Calorimeters are attractive in our field for various reasons:

In contrast with magnet spectrometers, in which the momentum resolution deteriorates linearly with the particle momentum, on most cases the calorimeter energy resolution improves as $1/\sqrt{E}$, where E is the energy of the incident particle. Therefore calorimeters are very well suited for high-energy physics experiments.

In contrast to magnet spectrometers, calorimeters are sensitive to all types of particles, charged and neutral. They can even provide indirect detection of neutrinos and their energy through a measurement of the event missing energy.

Calorimeters are commonly used for trigger purposes since they can provide fast signals that are easy to process and interpret.

They are space and therefore cost effective. Because the shower length increases only logarithmically with energy, the detector thickness needs to increase only logarithmically with the energy of the particles. In contrast for a fixed momentum resolution, the bending power BL^2 of a magnetic spectrometer must increase linearly with the particle momentum.

C.W. Fabjan and F. Gianotti, Rev. Mod. Phys., Vol. 75, N0. 4, October 2003