FISICA DE LA INTERACCIONES FUNDAMENTALES

1ER CUATRIMESTRE 2026

CLASE 4

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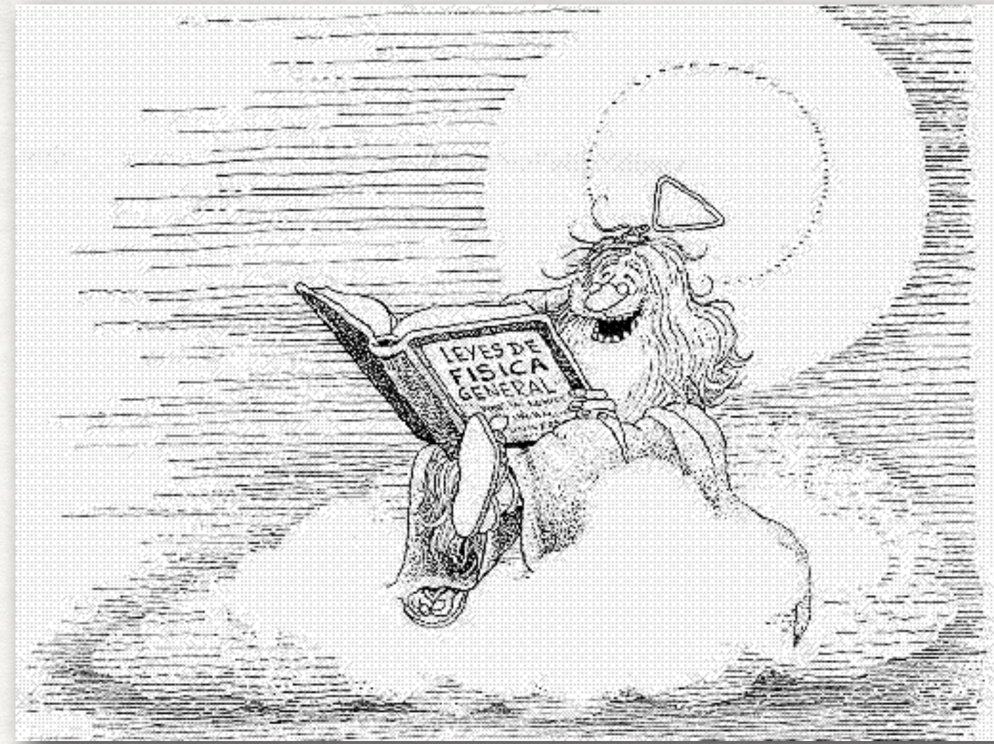
CLASE 4: Modelo de quarks y color.

modelo de quarks (1964): (de la clase 3)

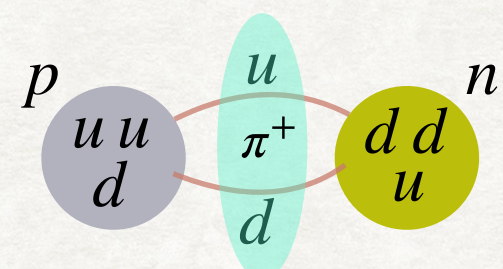


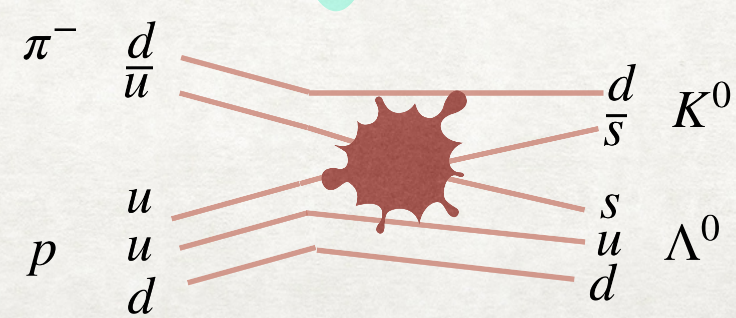
los quarks: tienen carga eléctrica fraccionaria
no existen de manera aislada
sólo se combinan de a tres o como $q\bar{q}$

	I_3	S	Q	B	J
u	1/2	0	2/3	1/3	1/2
d	−1/2	0	−1/3	1/3	1/2
s	0	−1	−1/3	1/3	1/2

	I_3	S	Q	B	
$u\bar{d}$	1	0	1	0	π^+
$d\bar{u}$	−1	0	−1	0	π^-
$u\bar{u}$, $d\bar{d}$	0	0	0	0	π^0

uuu	3/2	0	2	1	Δ^{++}	$I=3/2$	
uud	1/2	0	1	1	Δ^+, p		$SU(2)_{u-d}$
udd	−1/2	0	0	1	Δ^0, n		
ddd	−3/2	0	−1	1	Δ^-	$I=3/2$	
dds	−1	−1	−1	1	Σ^{*-}, Σ^-		$SU(2)_{d-s}$
dss	−1/2	−2	−1	1	Ξ^{*-}, Ξ^-		
sss	0	−3	−1	1	Ω^-	$I=3/2$	
ssu	1/2	−2	0	1	Ξ^{*0}, Ξ^0		$SU(2)_{u-s}$
suu	1	−1	1	1	Σ^{*+}, Σ^+		
uds	0	−1	0	1	Λ^0, Σ^0		





CLASE 4: Modelo de quarks y color.

funciones de onda de SU(3):

partículas spin 1/2 requieren simetría definida ante permutaciones

$SU(2) \qquad 2 \otimes 2 = 3_S + 1_A$

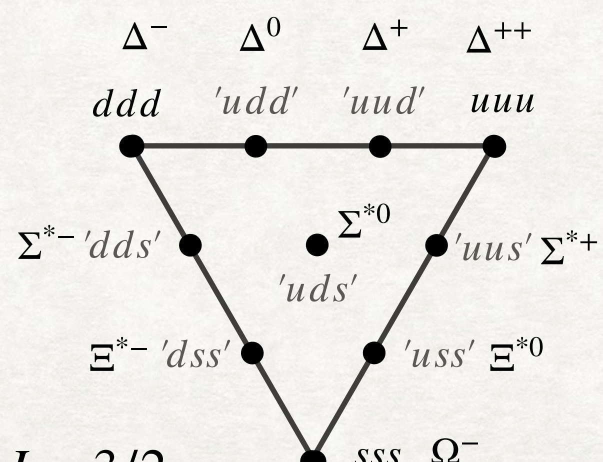
	S	A
$u\ u$	uu	
$u\ d$, $d\ u$	$\frac{1}{\sqrt{2}}(ud + du)$	$\frac{1}{\sqrt{2}}(ud - du)$
$d\ d$	dd	
$s\ d$, $d\ s$	$\frac{1}{\sqrt{2}}(sd + ds)$	$\frac{1}{\sqrt{2}}(sd - ds)$
$s\ s$	ss	
$s\ u$, $u\ s$	$\frac{1}{\sqrt{2}}(us + su)$	$\frac{1}{\sqrt{2}}(us - su)$

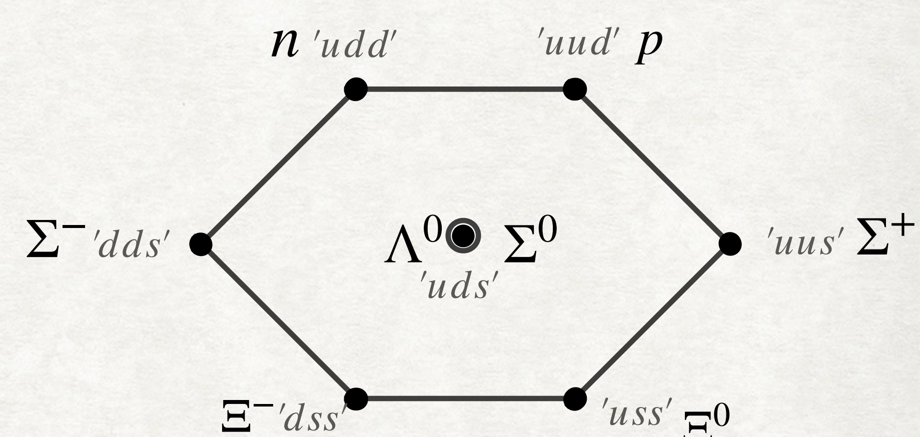
$2 \otimes 2 \otimes 2 \ = 4_S + 2_{MA} + 2_{MS}$

	S	MA	MS	
$u\ u\ u$	uuu			$I_3 = \frac{3}{2}$
$u\ u\ d$, $u\ d\ u$, $d\ u\ u$	$\frac{1}{\sqrt{3}}(uud + udu + duu)$	$\frac{1}{\sqrt{2}}(ud - du)u$	$\frac{1}{\sqrt{3}}[\frac{(ud+du)u}{\sqrt{2}} - \sqrt{2}uud]$	$I_3 = \frac{1}{2}$
$d\ d\ u$, $d\ u\ d$, $u\ d\ d$	$\frac{1}{\sqrt{3}}(ddu + dud + udd)$	$\frac{1}{\sqrt{2}}(ud - du)d$	$\frac{-1}{\sqrt{3}}[\frac{(ud+du)d}{\sqrt{2}} - \sqrt{2}ddu]$	$I_3 = -\frac{1}{2}$
$d\ d\ d$	ddd			$I_3 = -\frac{3}{2}$

$SU(3) \qquad 3 \otimes 3 = 6_S + \tilde{3}_A$

$3 \otimes 3 \otimes 3 = 10_S + 8_{MS} + 8_{MA} + 1_A$





$|\chi^{3/2}_{SU(2)} >$

$|3/2> = |\uparrow\uparrow\uparrow>$

$|1/2> = \frac{1}{\sqrt{3}}(\uparrow\uparrow\downarrow + \uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow)$

$|-1/2> = \frac{1}{\sqrt{3}}(\downarrow\downarrow\uparrow + \downarrow\uparrow\downarrow + \uparrow\downarrow\downarrow)$

$|-3/2> = |\downarrow\downarrow\downarrow>$

$J = 3/2$

$|\psi> = |\phi^{3/2}_{SU(3)}> |\chi^{3/2}_{SU(2)}>$

$|\psi>_S = \frac{1}{\sqrt{2}}[|\phi_{MS}>|\chi_{MS}> + |\phi_{MA}>|\chi_{MA}>]$ ✔

$|\psi>_A = \frac{1}{\sqrt{2}}[|\phi_{MS}>|\chi_{MA}> - |\phi_{MA}>|\chi_{MS}>]$

CLASE 4: Modelo de quarks y color.

momentos magnéticos:

propiedad bien característica partículas ~*determina como de acopla a* $\vec{B}$

definición clásica μ ~ corriente en una espira, extiende en términos de $\vec{L}$

ec. de Dirac predice correctamente el μ para e^-, μ^- (e^+, μ^+) *(con nueve cifras significativas!)*

$$\mu = \frac{e}{2m} \qquad (\hbar = c = 1)$$

pero falla para $p, n, \ldots$ momento magnético "anómalo"

(Otto Stern 1933)

$$\mu_q = Q_q \frac{e}{2m_q} \qquad \mu_p = \sum_q < p \uparrow | \mu_q \sigma_3 | p \uparrow > \qquad \mu_n = \sum_q < n \uparrow | \mu_q \sigma_3 | n \uparrow >$$

$$m_u = ? \quad m_d = ? \qquad m_u \simeq m_d \qquad \left. \frac{\mu_p}{\mu_n} \right|_{\psi_S} = -\frac{3}{2} \qquad -1.45989806(34)$$

$$\left. \frac{\mu_n}{\mu_p} \right|_{\psi_A} = \frac{1}{2}$$

CLASE 4: Modelo de quarks y color.

color:

$$|\psi> = |\phi^{3/2}_{SU(3)}> |\chi^{3/2}_{SU(2)}> |\psi_c>$$

decuplete incluye $I = 3/2$, y todas ellas tiene $J = 3/2$

$$|\psi> = \frac{1}{\sqrt{2}}[|\phi_{MS}> |\chi_{MS}> + |\phi_{MA}> |\chi_{MA}>]|\psi_c>$$

valor medido de μ_p/μ_n requiere $|\psi>_S$

quién antisimetriza la $|\psi>$ de los hadrones?

$$3 \otimes 3 \otimes 3 = 10_S + 8_{MS} + 8_{MA} + 1_A$$

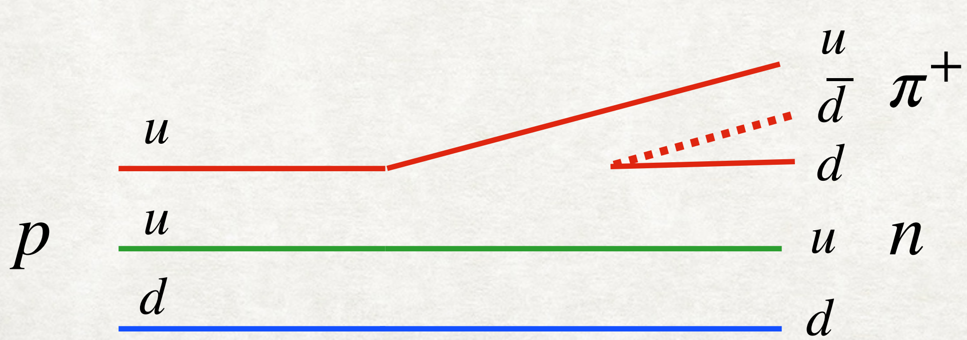
$$3 \otimes \overline{3} = 8_S + 1_A$$

$$\begin{pmatrix} R \\ B \\ G \end{pmatrix}$$

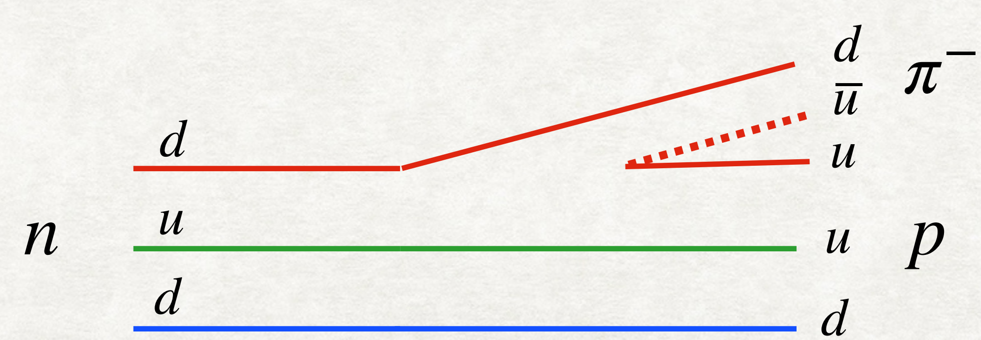
$$|\psi_c> = \frac{1}{\sqrt{6}}[RGB - RBG + GBR - GRB + BRG - BGR]$$

singlete de color ≡ sin color

las interacciones fuertes "aborrecen" el color explícito

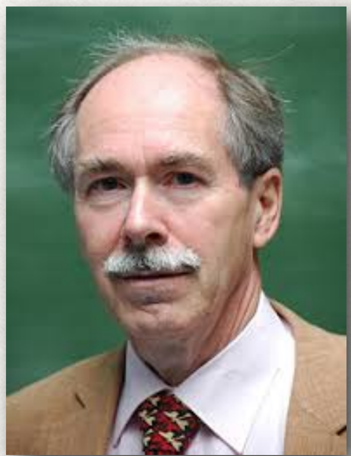


$$p + p \to d + \pi^+$$



$$n + p \to d + \pi^-$$

G. 't Hooft



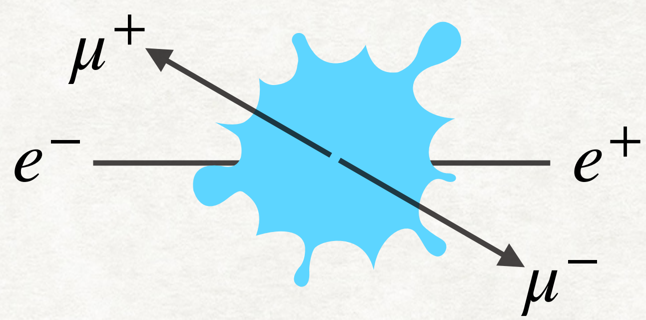
QCD

CLASE 4: Modelo de quarks y color.

evidencias del color:

además el indicio estadístico, y anteriores a la formulación de QCD

$$e^- + e^+ \to \mu^- + \mu^+$$



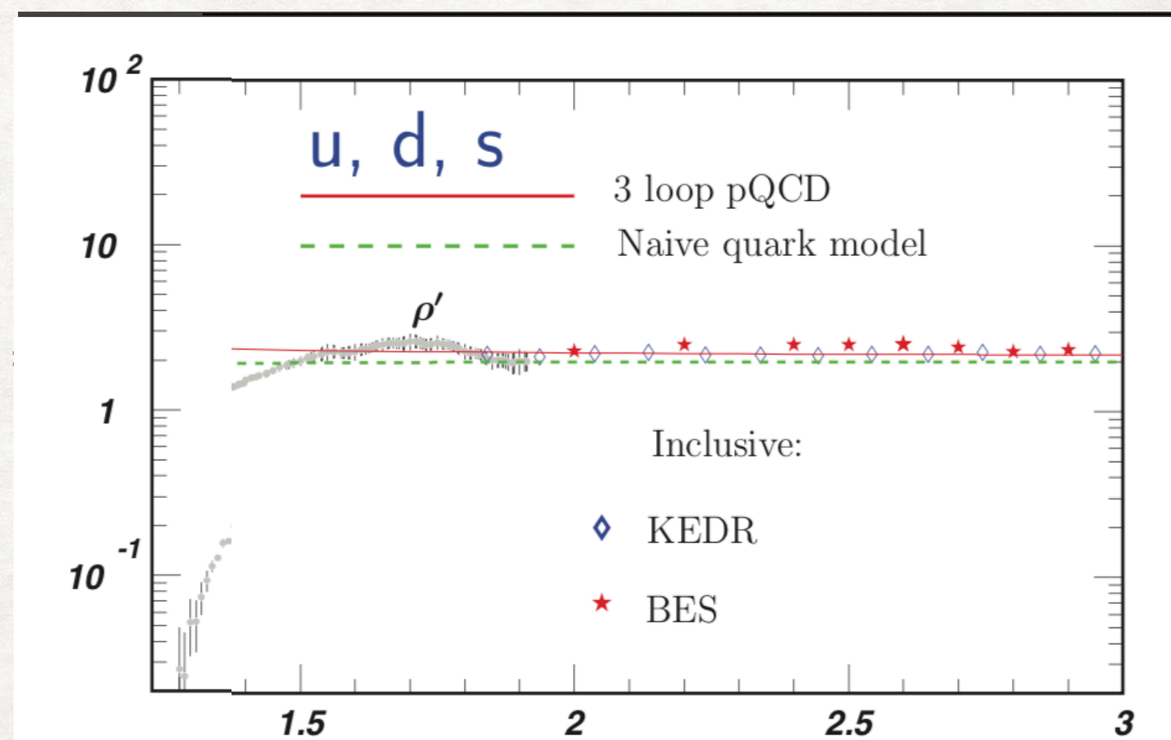
$$\sigma = \frac{\pi\alpha^2}{3E^2} \qquad (m_e = m_\mu = 0)$$

$$e^- + e^+ \to u + \bar{u} \;\to hadrones$$
$$\to d + \bar{d}$$
$$\to s + \bar{s}$$

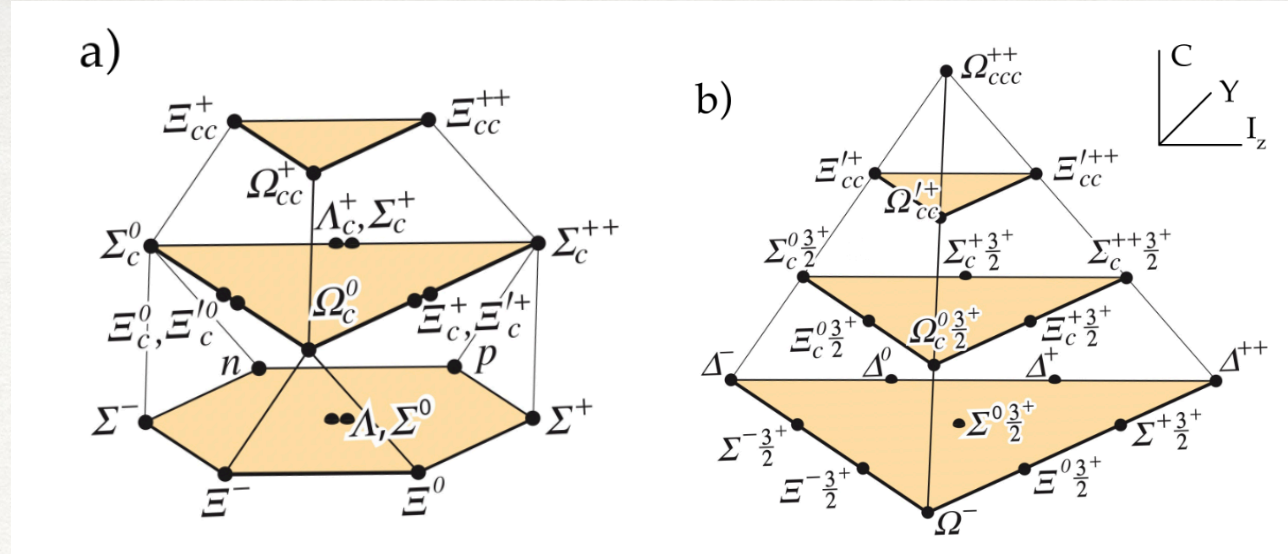
$$\sigma = \frac{\pi\alpha^2}{3E^2} Q_q^2$$

$$\frac{\sigma(e^+ + e^- \to hadrones)}{\sigma(e^+ + e^- \to \mu^+ + \mu^-)} = \sum_q Q_q^2 = 4/9 + 1/9 + 1/9 = 2/3$$

$$= \sum_{colores} \sum_q Q_q^2 = 3(4/9 + 1/9 + 1/9)$$



CLASE 4: Modelo de quarks y color.



evidencias del color:

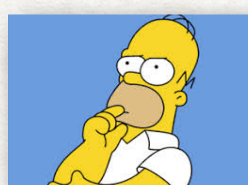
$$R = \sum_{colores} \sum_{q} Q_q^2 = 3(4/9 + 1/9 + 1/9) = 2$$

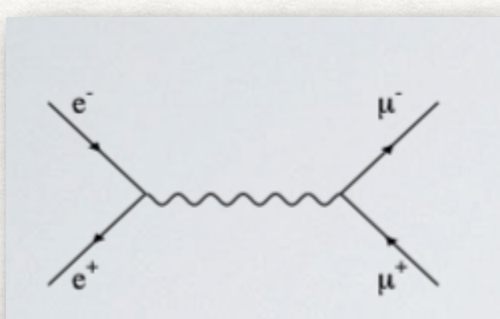
1974 $$R = \sum_{colores} \sum_{q} Q_q^2 = 3(4/9 + 1/9 + 1/9 + 4/9) = 3.33$$ $m_c = 1.6\,GeV$

1977 $$R = \sum_{colores} \sum_{q} Q_q^2 = 3(4/9 + 1/9 + 1/9 + 4/9 + 1/9) = 3.66$$ $m_b = 4.5\,GeV$

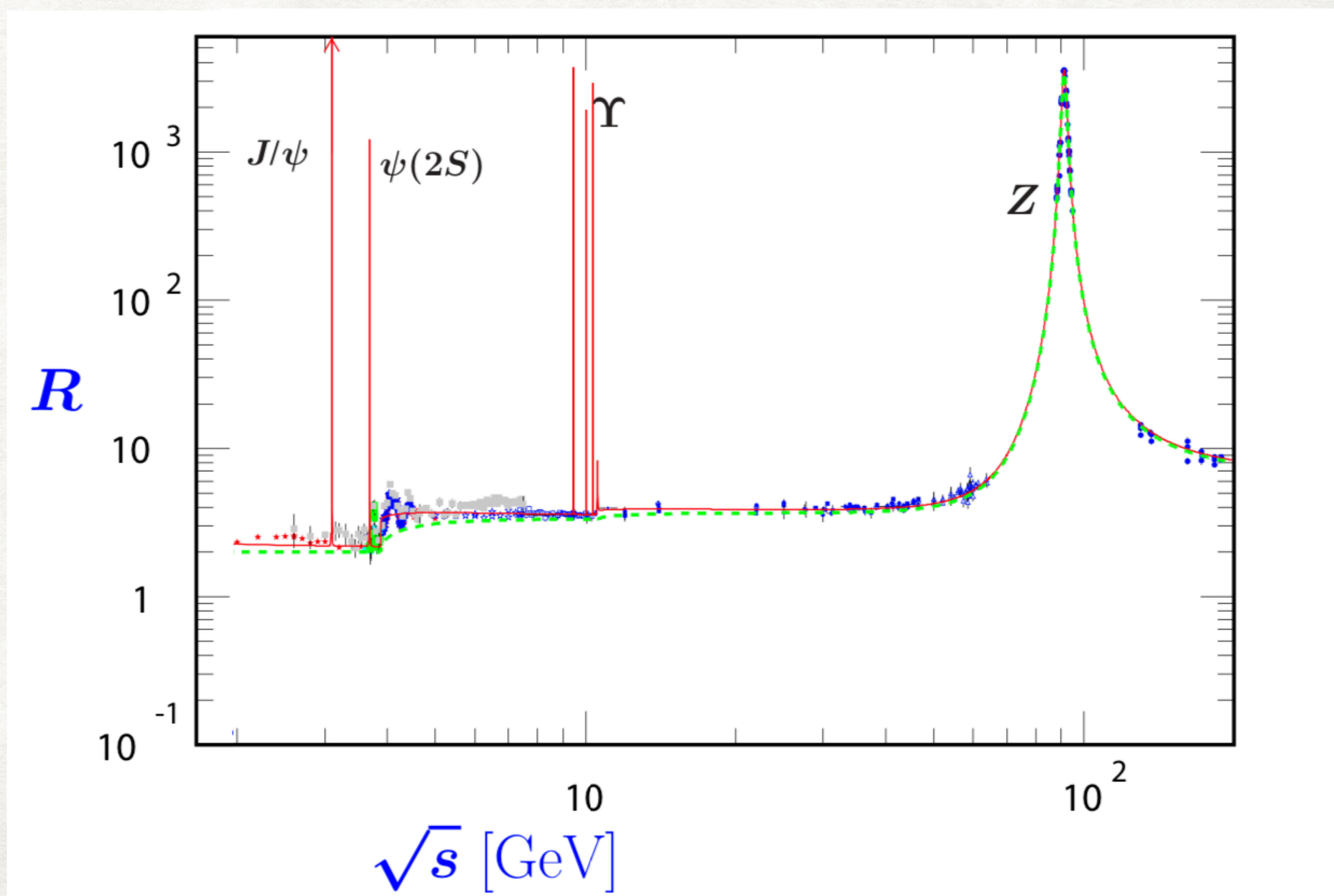
1995 $m_t = 178\,GeV$

$2/3$	u	c	t
$-1/3$	d	s	b
-1	e	μ	τ
0	ν_e	ν_μ	ν_τ



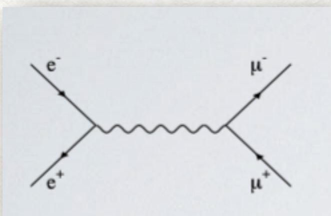


$$\sim \frac{1}{M^2 - s}$$

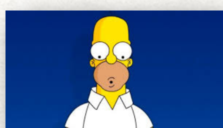


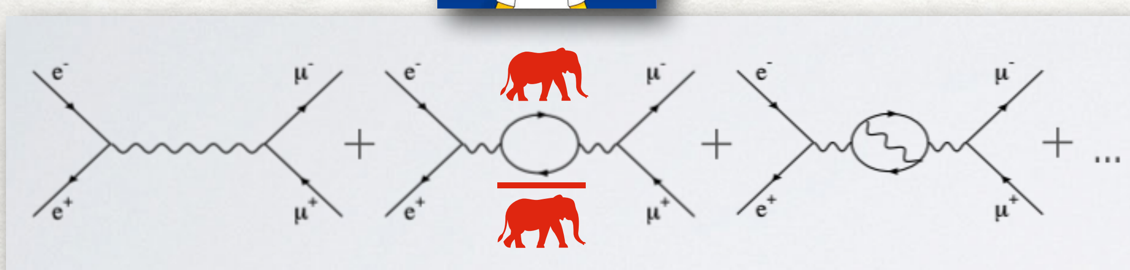
CLASE 4: Modelo de quarks y color.

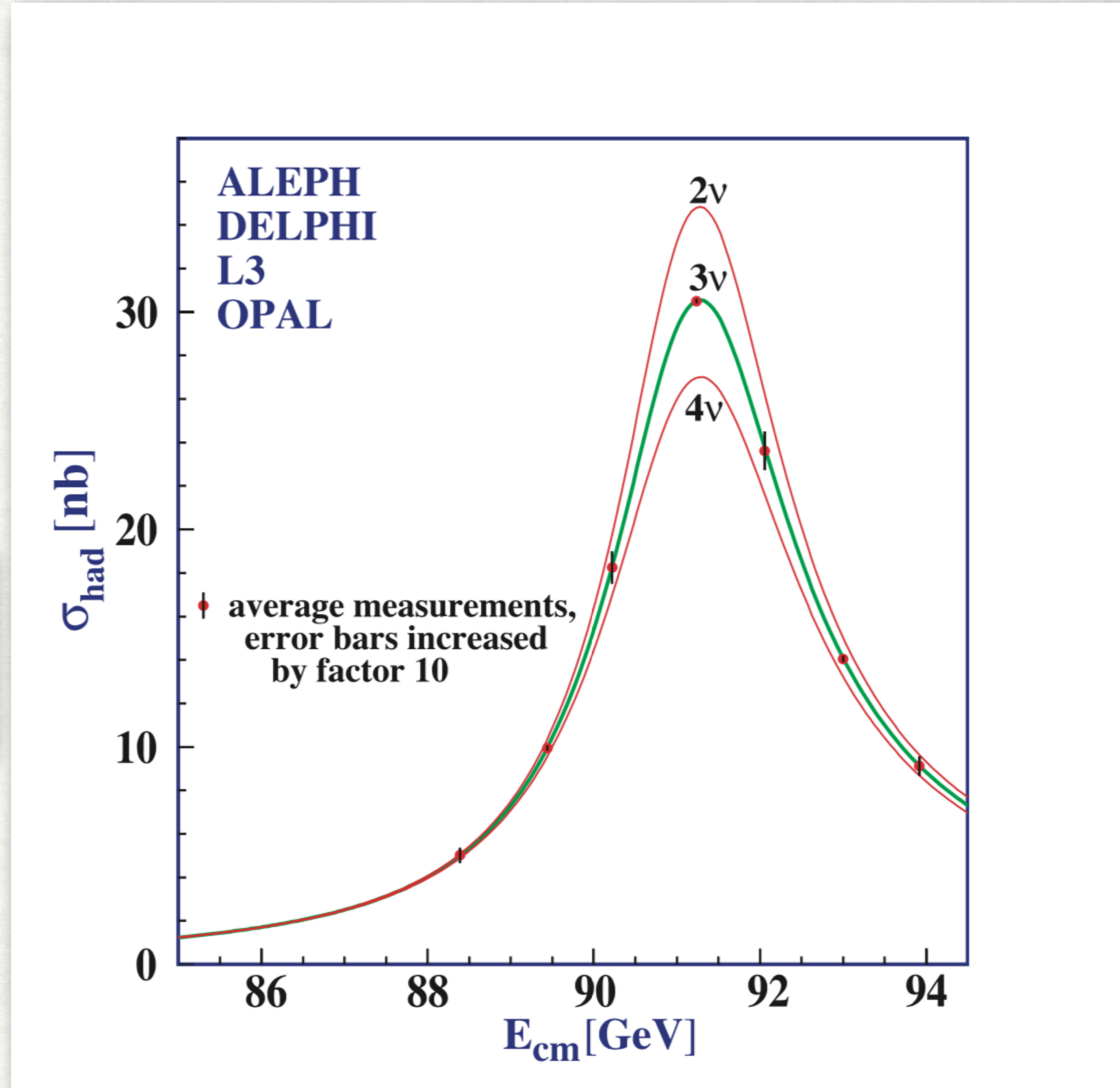
evidencias del color:



$$\sigma = \frac{\pi\alpha^2}{3E^2}$$



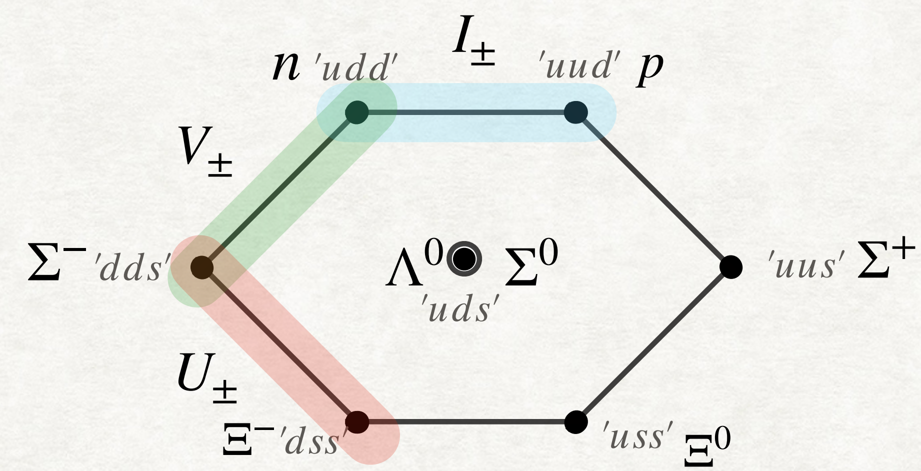




CLASE 4: Clasificación de partículas.

funciones de onda de los octetes SU(3):

$$\sigma_\pm \equiv \frac{1}{2}(\sigma_1 \pm i\sigma_2) \qquad \sigma_+ | d > = | u > \qquad \sigma_- | u > = | d >$$



MA	MS	
$\frac{1}{\sqrt{2}}(ud - du)u$	$\frac{1}{\sqrt{3}}[\frac{(ud + du)u}{\sqrt{2}} - \sqrt{2}uud]$	$I_3 = \frac{1}{2}$
$\frac{1}{\sqrt{2}}(ud - du)d$	$\frac{-1}{\sqrt{3}}[\frac{(ud + du)d}{\sqrt{2}} - \sqrt{2}ddu]$	$I_3 = -\frac{1}{2}$

$$\sigma_\pm^{2\otimes2\otimes2} \equiv \underline{\sigma_\pm \mathbb{1}\,\mathbb{1}} + \mathbb{1}\sigma_\pm\mathbb{1} + \mathbb{1}\,\mathbb{1}\sigma_\pm \qquad \sigma_-^{2\otimes2\otimes2} | \frac{1}{2}, \frac{1}{2} >_{MS} = | \frac{1}{2}, -\frac{1}{2} >_{MS}$$

$$\sigma_-^{2\otimes2\otimes2} | \frac{1}{2}, \frac{1}{2} >_{MS} = \sigma_-^{2\otimes2\otimes2} \frac{1}{\sqrt{6}}[\underline{udu} + \underline{duu} - \underline{2uud}] = \frac{1}{\sqrt{6}}[\underline{ddu} - \underline{2dud} + ddu - 2udd + udd + dud]$$

$$= \frac{1}{\sqrt{6}}[-dud - udd + 2ddu] = \frac{-1}{\sqrt{6}}[(du + ud)d - 2ddu]$$

$$SU(2) \to SU(3) \qquad I_\pm \equiv \frac{1}{2}(\lambda_1 \pm i\lambda_2) = \begin{pmatrix} \sigma_\pm^{11} & \sigma_\pm^{12} & 0 \\ \sigma_\pm^{21} & \sigma_\pm^{22} & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad u \leftrightarrow d \qquad V_\pm \equiv \frac{1}{2}(\lambda_4 \pm i\lambda_5) = \begin{pmatrix} \sigma_\pm^{11} & 0 & \sigma_\pm^{12} \\ 0 & 0 & 0 \\ \sigma_\pm^{21} & 0 & \sigma_\pm^{22} \end{pmatrix} \quad u \leftrightarrow s$$

$$U_\pm \equiv \frac{1}{2}(\lambda_6 \pm i\lambda_7) = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \sigma_\pm^{11} & \sigma_\pm^{12} \\ 0 & \sigma_\pm^{21} & \sigma_\pm^{22} \end{pmatrix} \quad d \leftrightarrow s$$