Particle Physics
The Standard Model
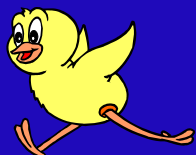
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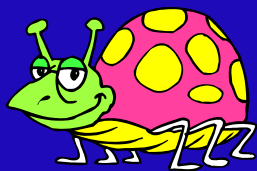
2. Quarks

- Quarks

- Colour

- Confinement

- Asymptotic Freedom

Quarks

up

down

charm

strange
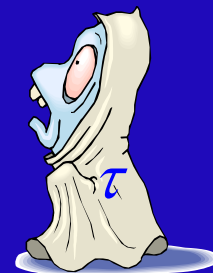
top

beauty

Leptons

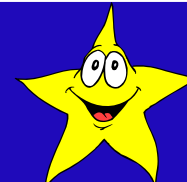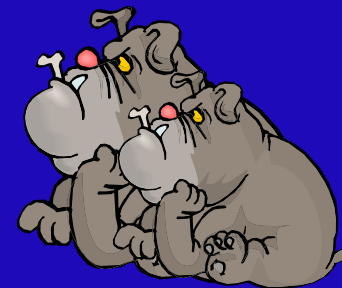electron

neutrino e

muon

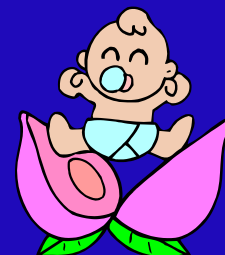neutrino μ

tau

neutrino τ

Bosons

photon

gluon

Z^0 $W^\pm$

Higgs

QUARKS

- **Strong Interactions** bind them into hadrons
- Not Observed as Free Particles ➡ **Confinement**
- Spin ½ ; Pointlike $(r \leq \text{few} \times 10^{-17} \text{ cm})$
- $Q_u = 2/3$; $Q_d = -1/3$

Family Structure:

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L \quad , \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L \quad , \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L$$

Mass eigenstates $\neq$ Flavour eigenstates

$$V_{\text{CKM}} \cdot V_{\text{CKM}}^{\dagger} = 1$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Why 3 ?

Light (MeV)	$m_u \sim 5$	$m_d \sim 8$	$m_s \sim 150$
Heavy (GeV)	$M_c \sim 1.2$	$M_b \sim 4.2$	$M_t \sim 178$

MESONS $\equiv q_1 \overline{q}_2$

$(L = 0)$

Spin:

$$\frac{1}{2} \otimes \frac{1}{2} \quad \longrightarrow \quad J = 0, 1$$

$J = 0$

$J = 1$
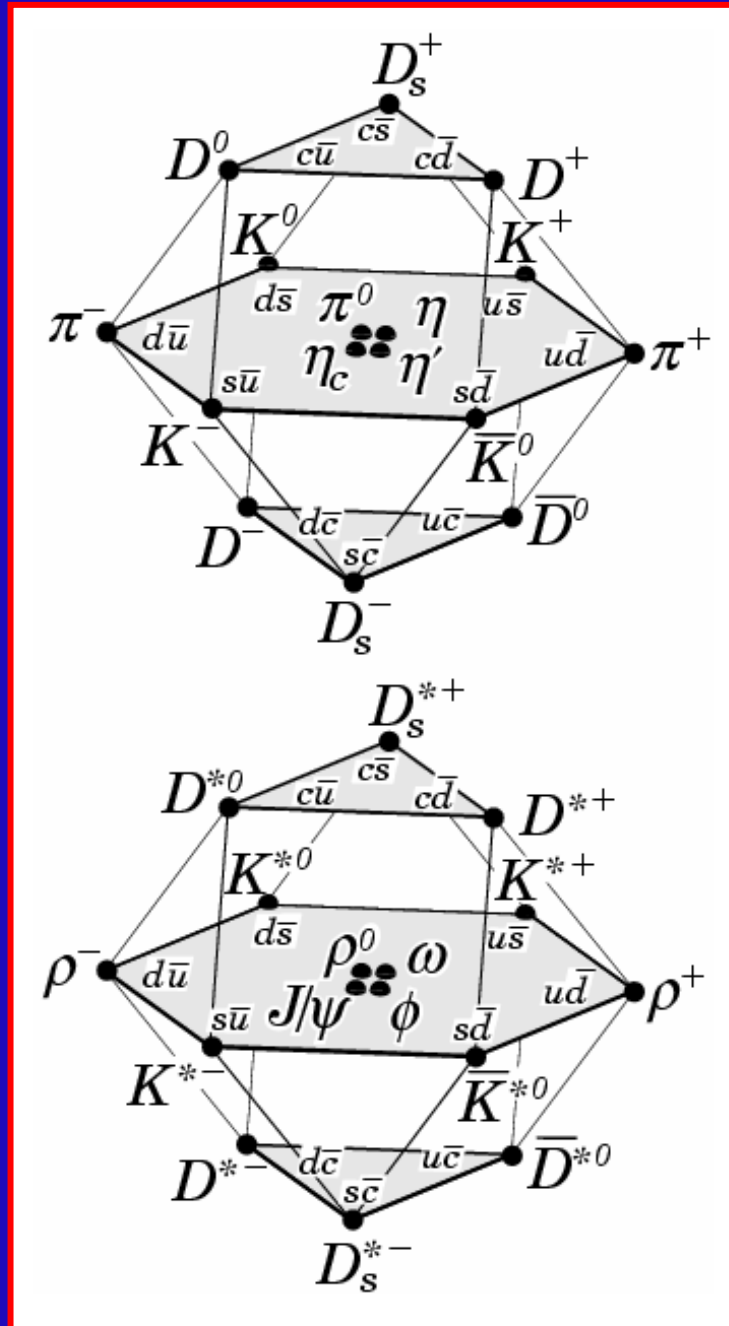
SU(4): u, d, s, c

BARYONS
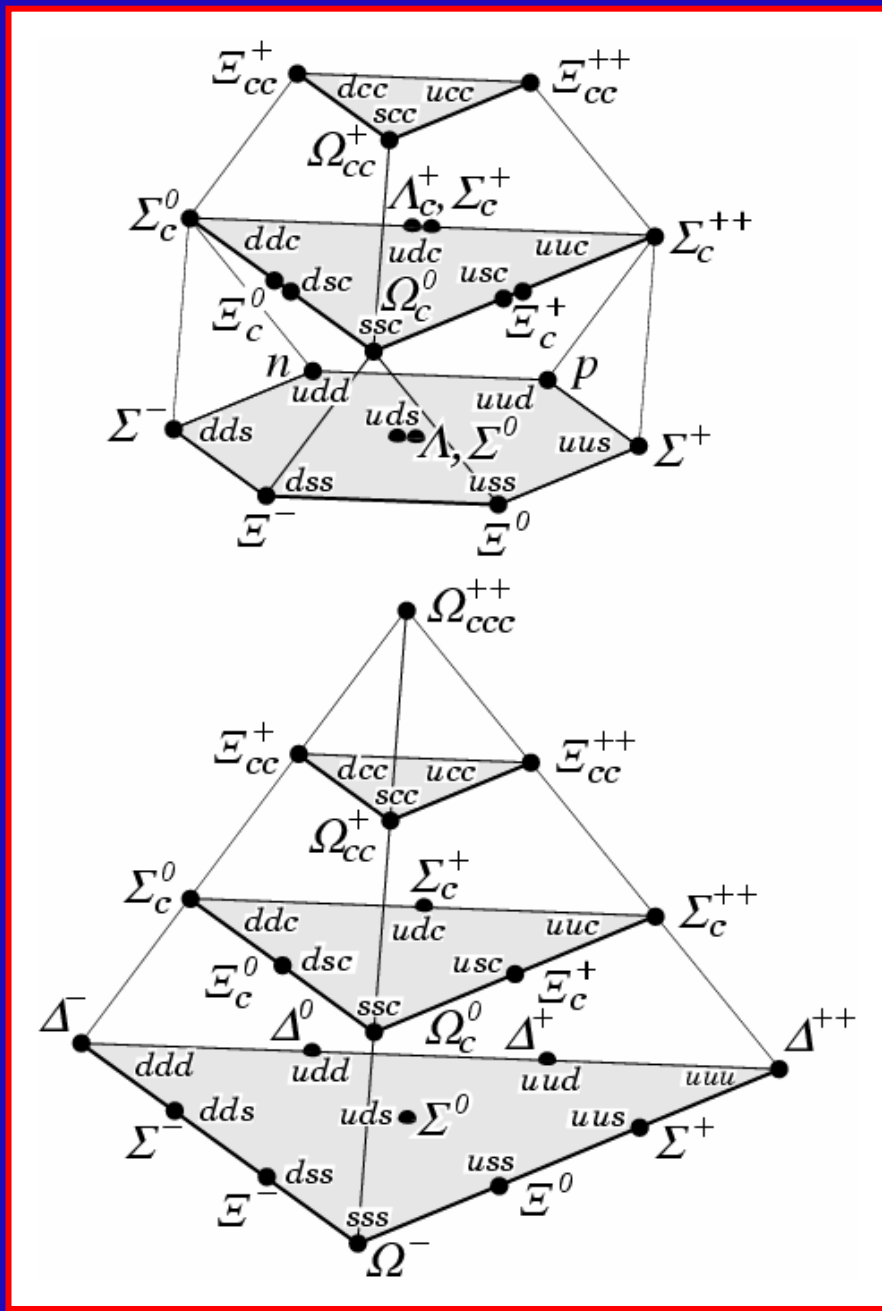
$$\equiv \ q_1 \ q_2 \ q_3$$

Baryon Number:

$$B\,(q_i) \ = \ \frac{1}{3}$$

Spin:

$$\frac{1}{2} \otimes \frac{1}{2} \otimes \frac{1}{2} \quad \longrightarrow \quad J = \frac{1}{2}, \frac{3}{2}$$

SU(4): u, d, s, c

$(L = 0)$

$J = \dfrac{1}{2}$

$J = \dfrac{3}{2}$

Hadronization Scale $\wedge_\chi \sim 1$ GeV

ISOSPIN: u, d $M_p = 938.3$ MeV ; $M_n = 939.6$ MeV $m_{u,d} \ll \wedge_\chi$

SU(3): u, d, s $M_\wedge = 1115.7$ MeV ; $M_{\Xi^0} = 1314.8$ MeV $m_s < \wedge_\chi$

SU(4): u, d, s, c $\Sigma_c = 2453$ MeV ; $\Omega_c^0 = 2704$ MeV $M_c \approx \wedge_\chi$

SU(5): u, d, s, c, b $M_{\wedge_b^0} = 5624$ MeV $M_b > \wedge_\chi$

SU(6): u, d, s, c, b, t $M_t = 178$ GeV $M_t \gg \wedge_\chi$

$$\tau(t)^{-1} \equiv \Gamma(t \to \text{all}) \approx \Gamma(t \to b\,W^+) \gg \wedge_\chi$$

The Top Quark has no time to Hadronize

CHARMONIUM

$\psi(2S)$

$\eta_c(2S)$ γ

hadrons

γ^* $\chi_{c0}(1P)$

γ

hadrons

hadrons

$\chi_{c1}(1P)$

γ

hadrons

$\chi_{c2}(1P)$

hadrons

γ

$\pi\pi$

η, π^0

γ

γ

γ

$J/\Psi(1S)$

$\eta_c(1S)$

hadrons   hadrons γ^* radiative

$J^{PC} = \quad 0^{-+} \qquad\qquad 1^{--} \qquad\qquad 0^{++} \qquad\qquad 1^{++} \qquad\qquad 2^{++}$

$L = 0 \qquad\qquad\qquad\qquad\qquad L = 1$
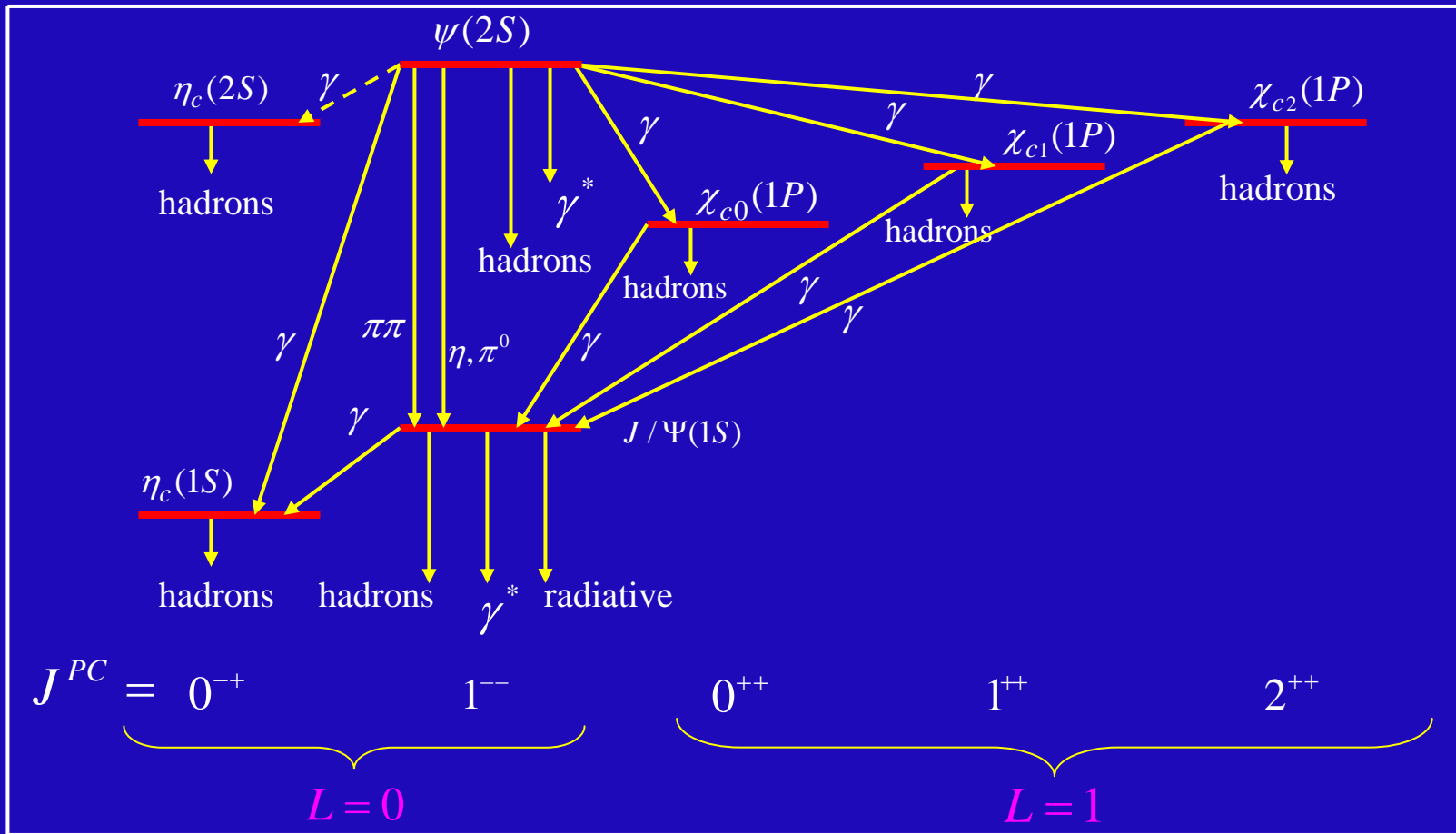
Bound $c\,\bar{c}$ **States**

$M_{\eta_c(1S)} = 2.980$ GeV ; $M_{\eta_c(2S)} = 3.594$ GeV

$M_{J/\Psi(1S)} = 3.097$ GeV ; $M_{\Psi(2S)} = 3.686$ GeV

$$V_{c\bar{c}}(r) = -C_F \frac{\alpha_s}{r} + k\,r$$

$$C_F = \frac{4}{3} \quad;\quad \alpha_s \simeq 0.21 \quad;\quad k \simeq 1\,\text{GeV fm}^{-1}$$

BOTTOMONIUM

$b\,\bar{b}$ States

$\alpha_s \simeq 0.18$

$\Upsilon\,(11020)$

$\Upsilon\,(10860)$

$\Upsilon\,(4S)$

$B\bar{B}$ threshold

$\eta_b(3S)$ $\Upsilon\,(3S)$ γ $\chi_{b0}(2P)$ $\chi_{b1}(2P)$ $\chi_{b2}(2P)$

hadrons $h_b(2P)$

hadrons γ

$\eta_b(2S)$ $\Upsilon\,(2S)$ γ $\chi_{b2}(1P)$

$h_b(1P)$ $\chi_{b0}(1P)$ $\chi_{b1}(1P)$

hadrons γ

$\eta_b(1S)$ $\Upsilon\,(1S)$

$J^{PC} =$ 0^{-+} 1^{--} 1^{+-} 0^{++} 1^{++} 2^{++}

$L = 0$ $L = 1$
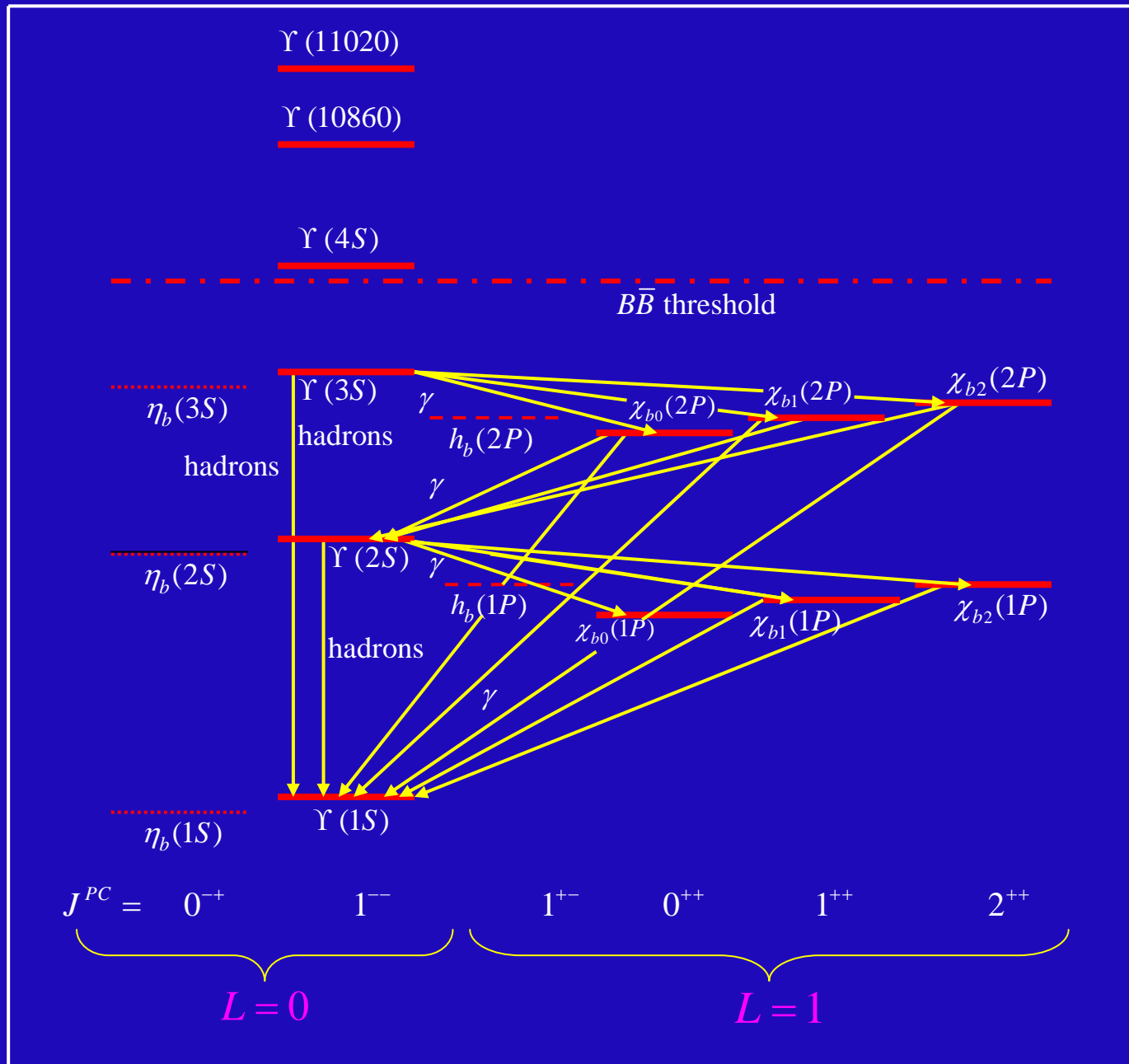
QUARKS HAVE COLOUR

$$\Delta^{++} = u^{\uparrow} u^{\uparrow} u^{\uparrow} \qquad (J = \tfrac{3}{2}, \; J_3 = \tfrac{3}{2})$$

Fermi Statistics ➡ $\Delta^{++} \approx \varepsilon^{\alpha\beta\gamma} u_{\alpha}^{\uparrow} u_{\beta}^{\uparrow} u_{\gamma}^{\uparrow}$

$$B \approx \varepsilon^{\alpha\beta\gamma} q_{\alpha}^{i} q_{\beta}^{j} q_{\gamma}^{k} \quad ; \quad M \approx \delta^{\alpha\beta} q_{\alpha}^{i} \overline{q}_{\beta}^{j} \qquad (i,j,k = u,d,s,\ldots \; ; \; \alpha,\beta,\gamma = 1,\ldots,Nc)$$

$$N_C = 3 \quad ➡ \quad q^i \; q^i \; q^i$$

We don´t see Colour Multiplets ➡ Hadrons are Colour Singlets

$(q\,q\,q , \; \overline{q}\,\overline{q}\,\overline{q} \; \text{and} \; q\,\overline{q} \; ; \; \text{BUT NOT} \; q\,q \; \text{and} \; q\,q\,q\,q)$

We don´t see Quarks ➡
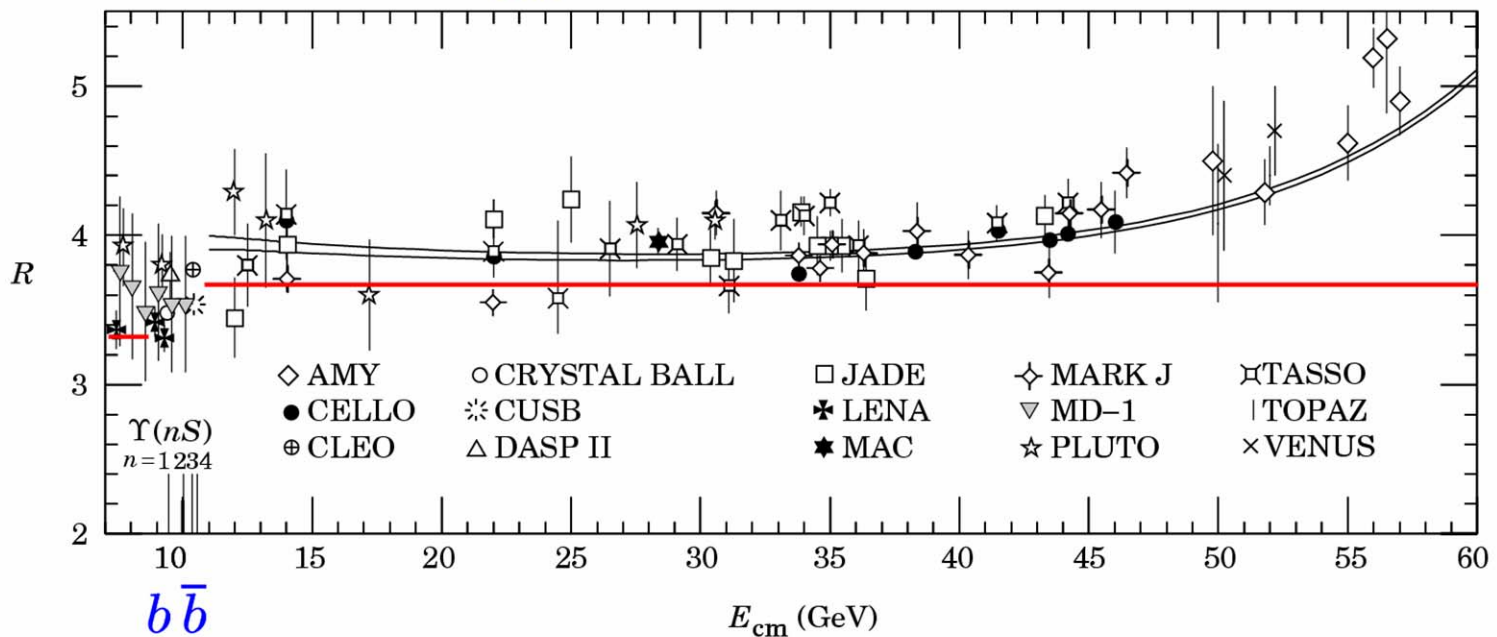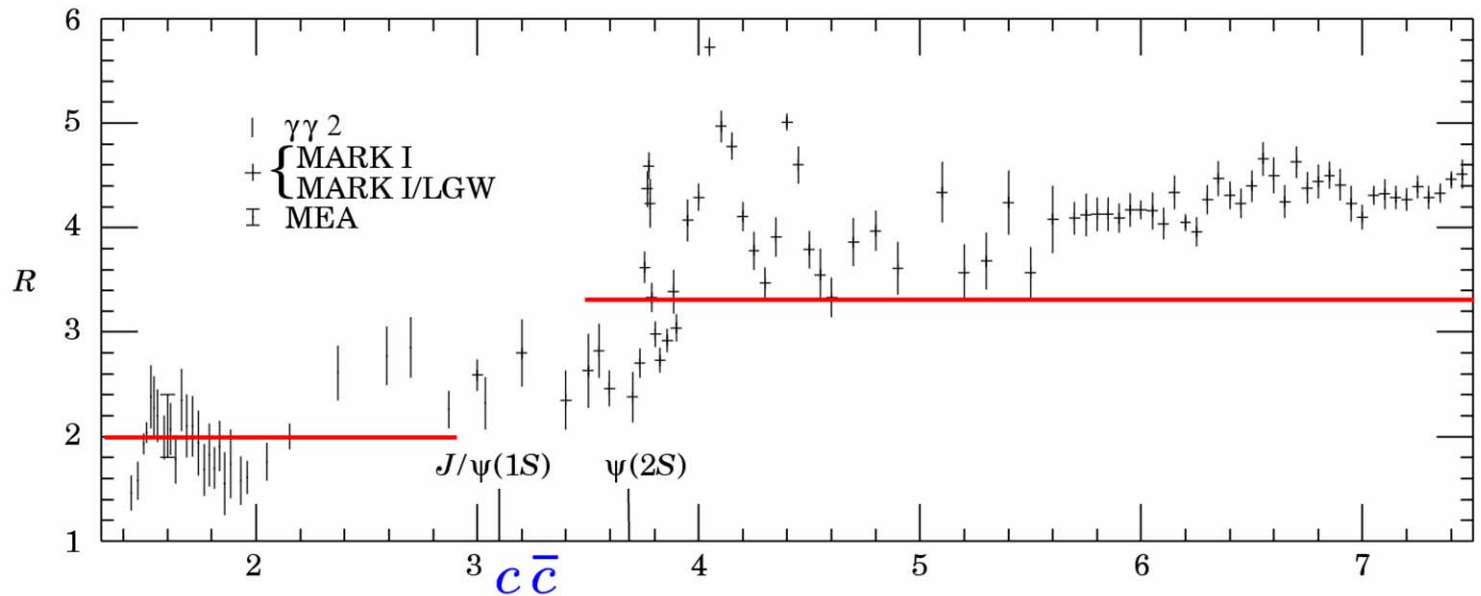
◆ Don´t exist ?

◆ **CONFINEMENT**

Z

q

q̄
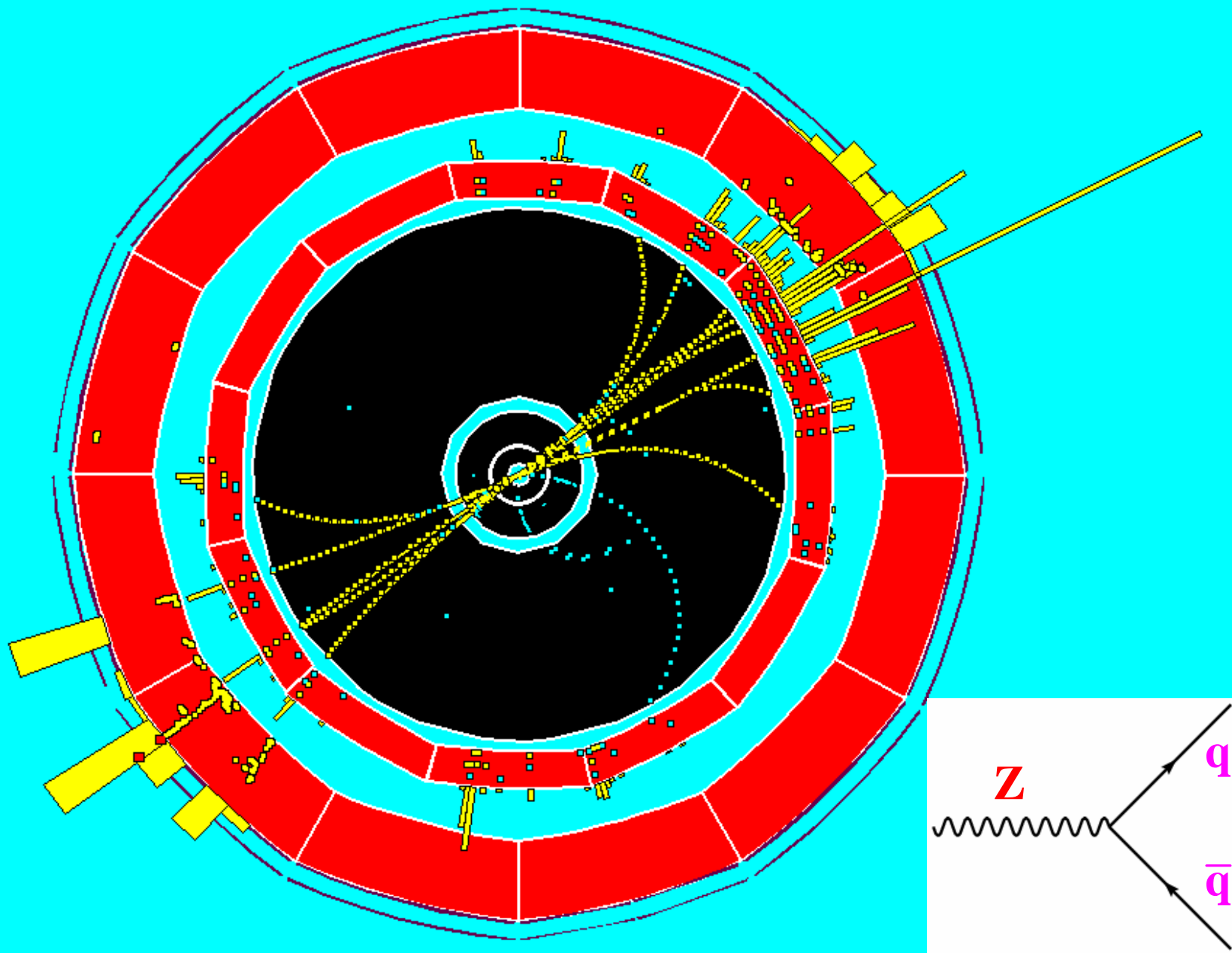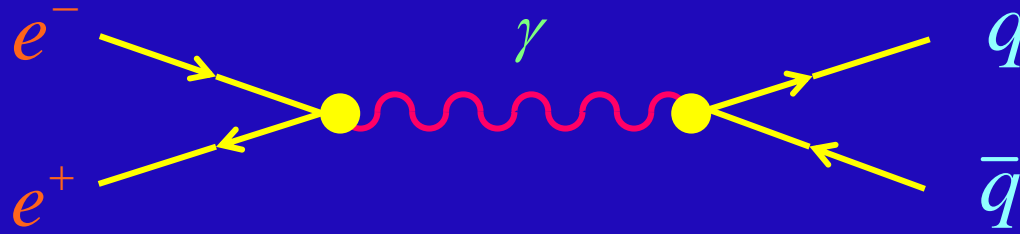
$$R \equiv \frac{\sigma(e^+ e^- \to \text{hadrons})}{\sigma(e^+ e^- \to \mu^+ \mu^-)} \simeq \frac{\sum_q \sigma(e^+ e^- \to q\bar{q})}{\sigma(e^+ e^- \to \mu^+ \mu^-)} \simeq N_C \sum_q Q_q^2$$
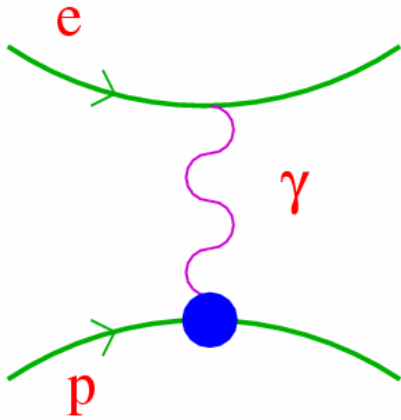
$$= \begin{cases} \dfrac{2}{3} \, N_C & , & (u, d, s) \\[2mm] \dfrac{10}{9} \, N_C & , & (u, d, s, c) \\[2mm] \dfrac{11}{9} \, N_C & , & (u, d, s, c, b) \end{cases}$$

$c\,\bar{c}$

$b\,\bar{b}$

AMY ◇　CRYSTAL BALL ○　JADE □　MARK J ✧　TASSO ⌗
CELLO ●　CUSB ☀　LENA ✦　MD–1 ▽　TOPAZ |
CLEO ⊕　DASP II △　MAC ✹　PLUTO ☆　VENUS ×

$\Upsilon(nS)$
$n = 1\,2\,3\,4$

E_{cm} (GeV)

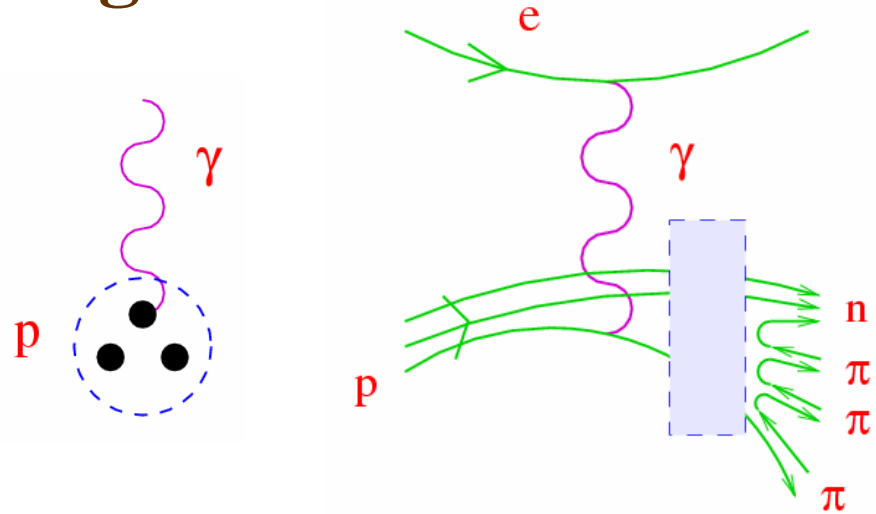The Standard Model   A. Pich - CERN Summer Lectures 2005

e p   Scattering

$\lambda = h / q$

Small E

High E

High-Energy hadronic processes are well described through the interactions of **free** constituent quarks

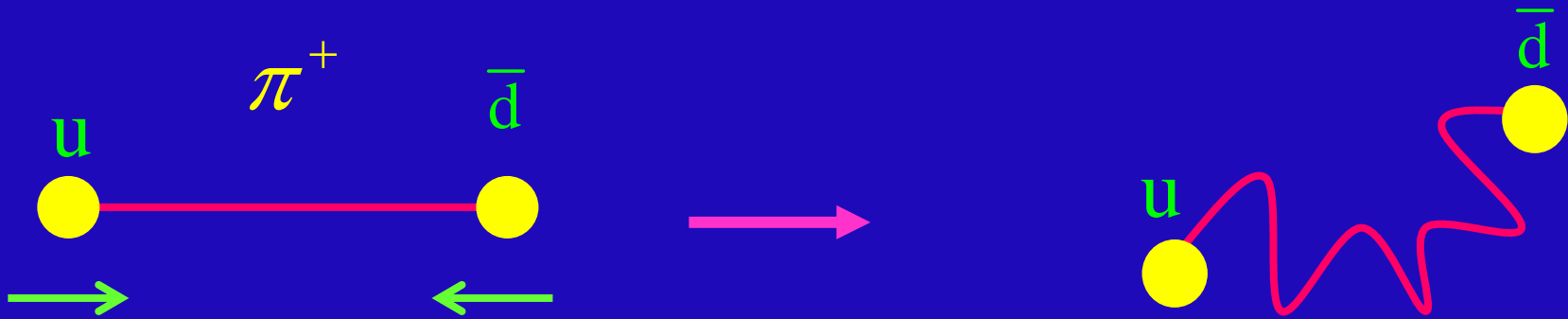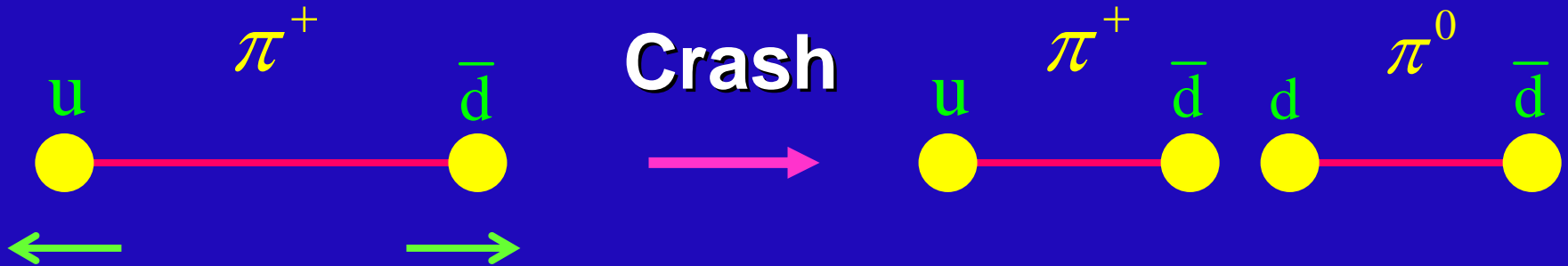$$\sigma \, (e^- p \to e^- X) \;\approx\; \sum_q P_q \;\; \sigma(e^- q \to e^- q)$$

ASYMPTOTIC FREEDOM:

$$\alpha_s \to 0 \qquad \text{at large E} \qquad \text{(short distances)}$$

CONFINEMENT:

Large $\quad \alpha_s \quad$ at small E $\qquad$ (large distances)

CONFINEMENT

ASYMPTOTIC   FREEDOM

ASYMPTOTIC FREEDOM:

$$\alpha_s \rightarrow 0 \qquad \text{at large E} \qquad \text{(short distances)}$$

CONFINEMENT:

$$\text{Large} \quad \alpha_s \quad \text{at small E} \qquad \text{(large distances)}$$

Quark Flavour (u, d, s, c, b, t)

Strong Interactions are
$\left\{ \begin{array}{l} \text{Flavour Independent} \\ \text{Flavour Conserving} \end{array} \right\}$
COLOURDYNAMICS

Weak Interactions change the Quark Flavour: FLAVOURDYNAMICS

Quarks   Leptons   Bosons

Quarks		Leptons		Bosons
up	down	electron	neutrino e	photon
charm	strange	muon	neutrino μ	gluon
top	beauty	tau	neutrino τ	Z^0 $W^\pm$
				Higgs