http://arxiv.org/pdf/0705.4264

Particle Physics
The Standard Model

Antonio Pich

IFIC, CSIC – Univ. Valencia

Antonio.Pich@ific.uv.es

2. Quarks

- Quarks
- Colour
- Confinement
- Asymptotic Freedom

Quarks

up

down

charm

strange

top

beauty

Leptons

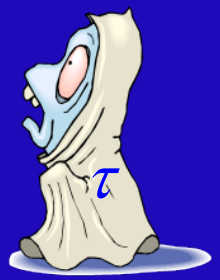
electron

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 ≠ Flavour eigenstates

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

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

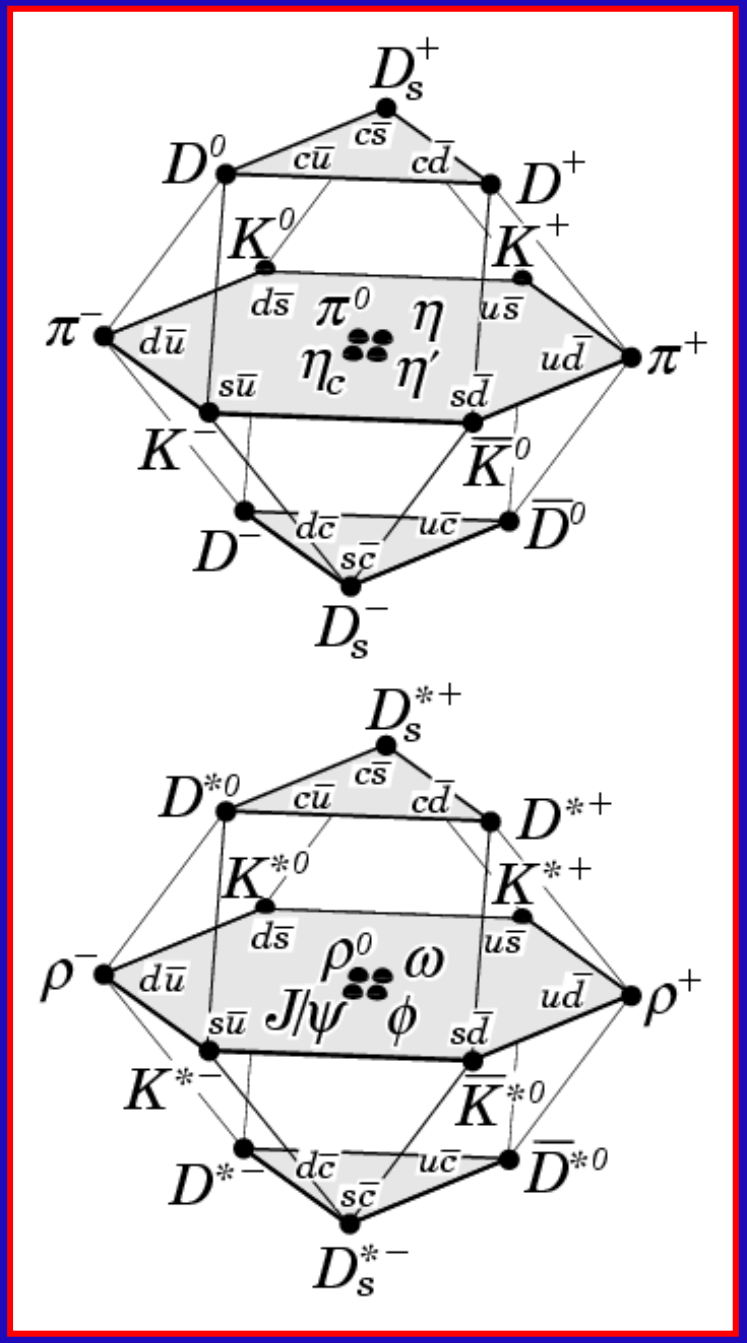
Why 3 ?

Light (MeV)	$m_u \sim 5$	$m_d \sim 8$	$m_s \sim 115$
Heavy (GeV)	$M_c \sim 1.2$	$M_b \sim 4.2$	$M_t \sim 171$

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

Spin:

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



$(L = 0)$

J = 0

J = 1

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

BARYONS

$$\equiv \; q_1 \; q_2 \; q_3$$

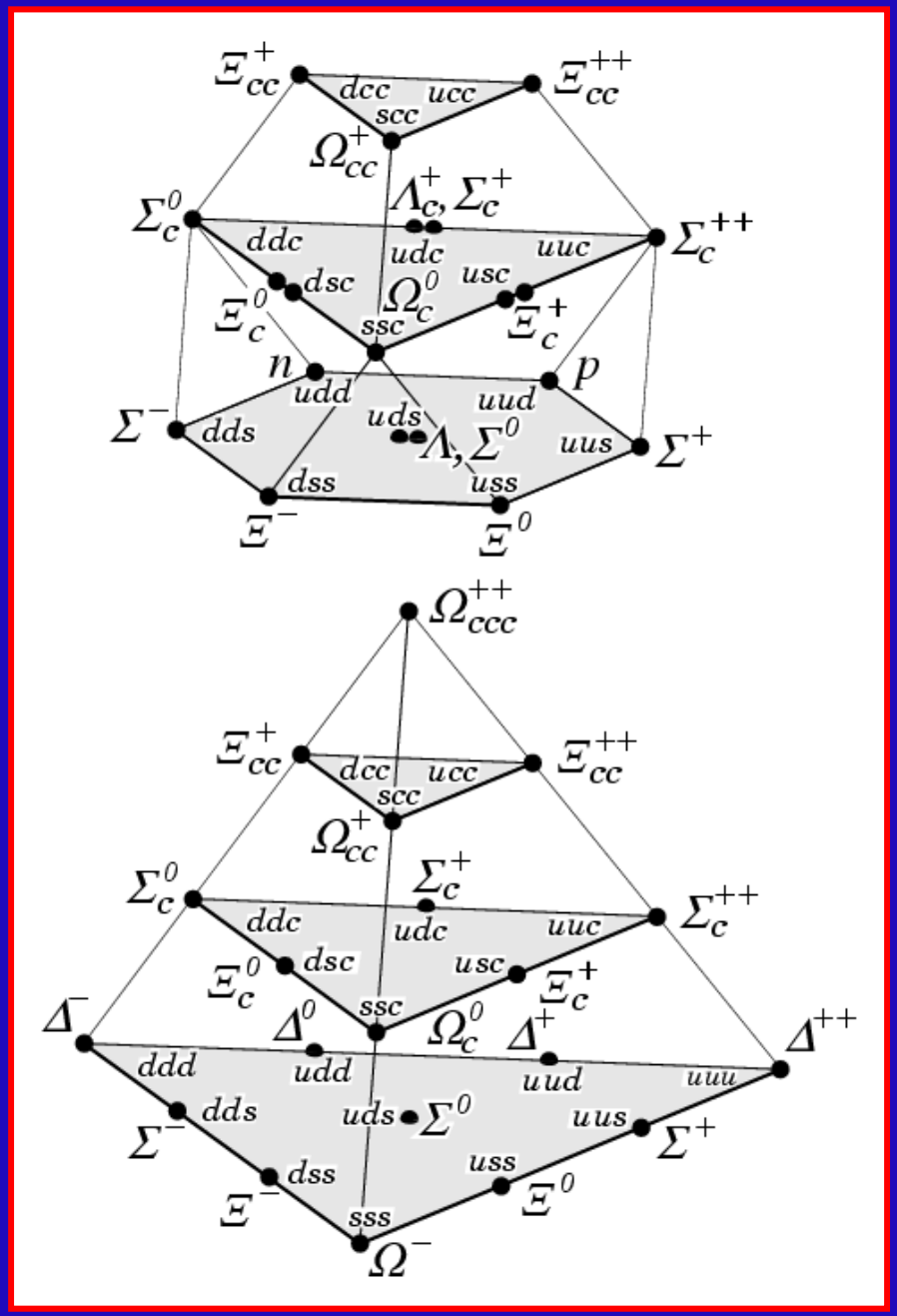
Baryon Number:

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

Spin:

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

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



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

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

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

SU(4): u, d, s, c $\quad \Sigma_c = 2453$ MeV ; $\Omega_c^0 = 2697.5$ MeV $\quad M_c \approx \Lambda_\chi$

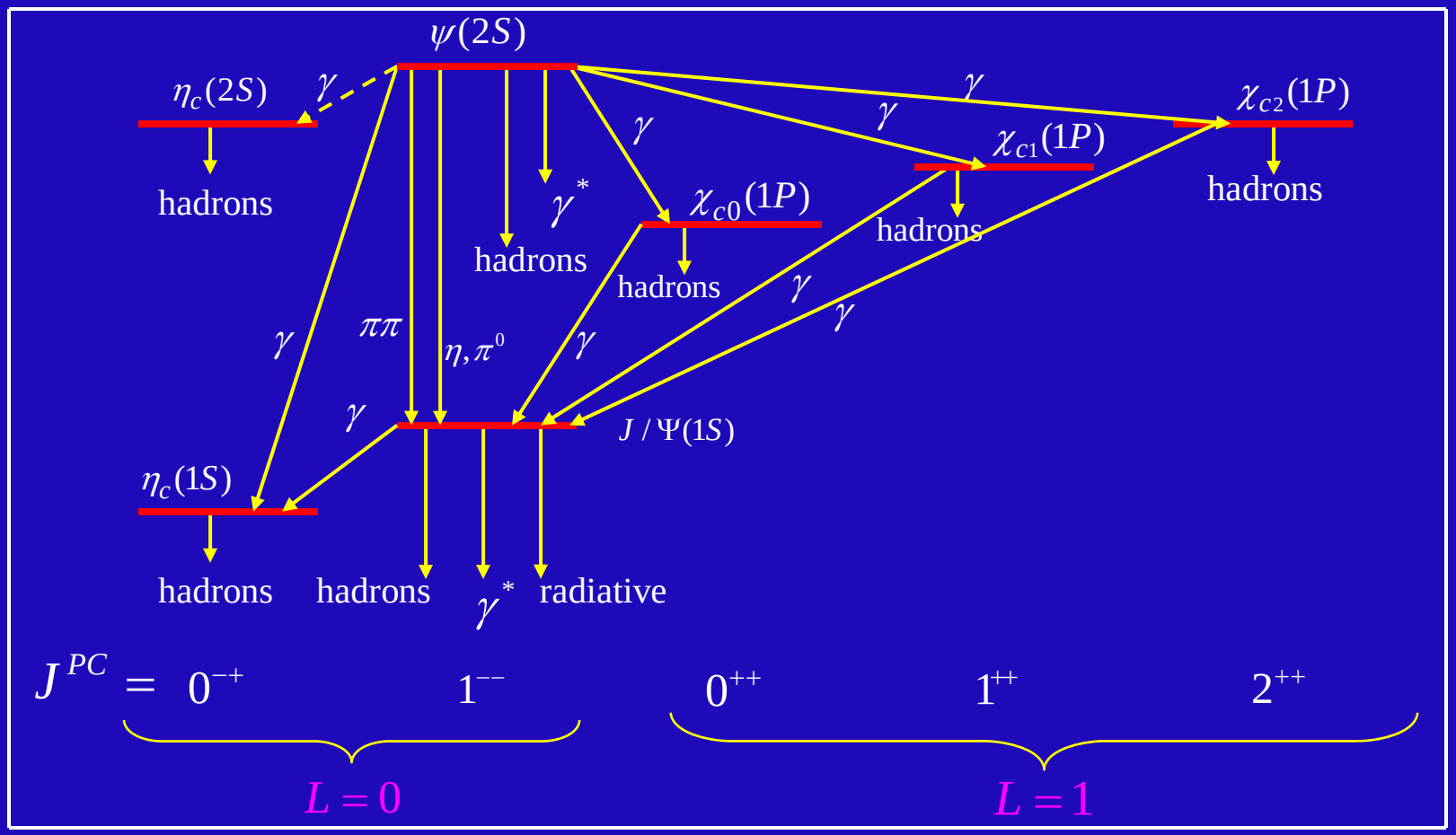
SU(5): u, d, s, c, b $\quad M_{\Lambda_b^0} = 5624$ MeV $\quad M_b > \Lambda_\chi$

SU(6): u, d, s, c, b, t $\quad M_t = 171$ GeV $\quad M_t \gg \Lambda_\chi$

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

The Top Quark has no time to Hadronize

MC-2008



Bound $c\bar{c}$ States

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

$M_{\eta_c(1S)} = 2.980$ GeV ; $M_{\eta_c(2S)} = 3.638$ GeV

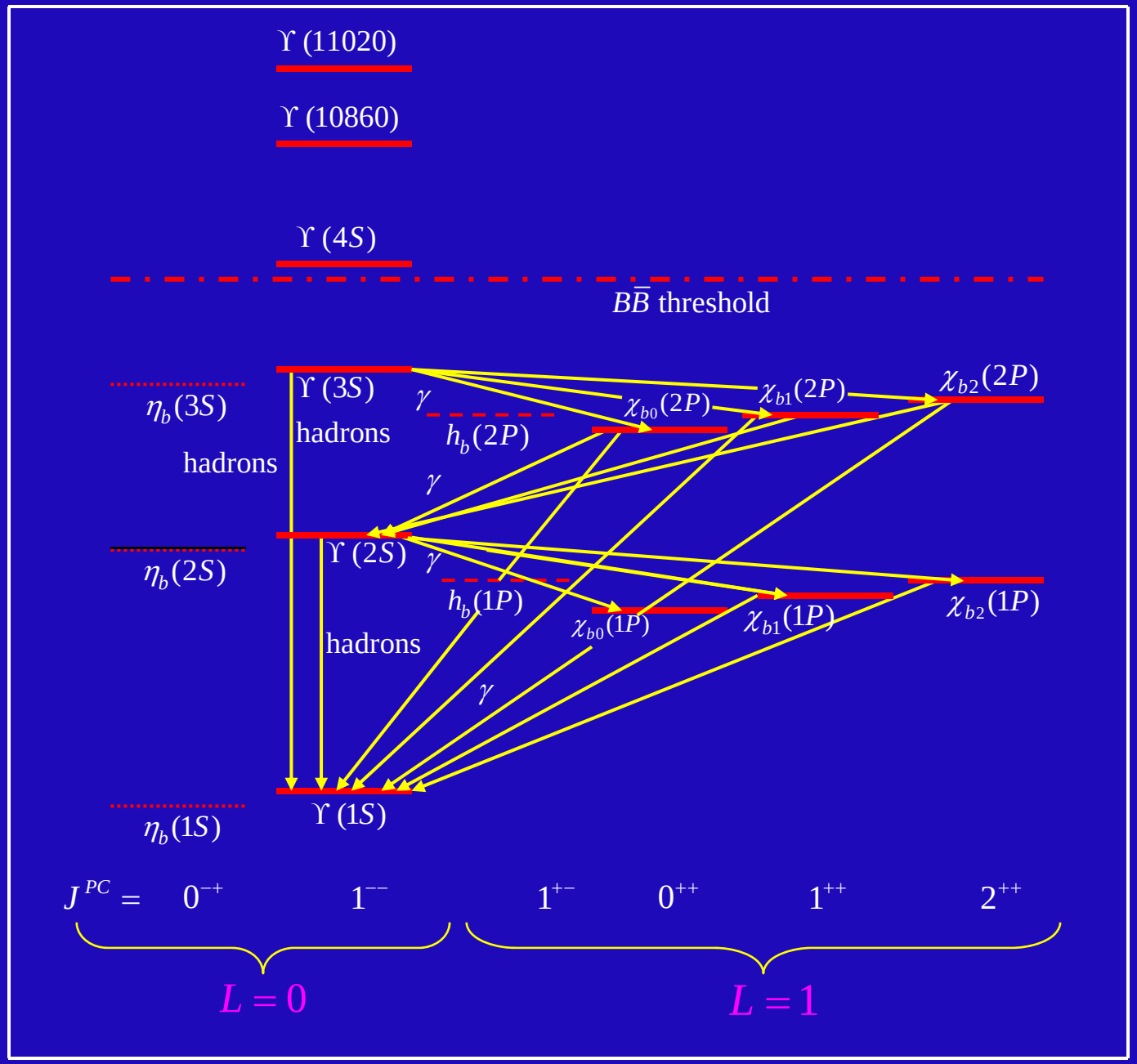
$M_{J/\Psi(1S)} = 3.097$ GeV ; $M_{\Psi(2S)} = 3.686$ GeV

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

Bottomonium

$b\bar{b}$ States

$\alpha_s \simeq 0.18$



QUARKS HAVE COLOUR

$\Delta^{++} = u^{\uparrow}\, u^{\uparrow}\, u^{\uparrow}$ $\quad (J = \frac{3}{2},\ J_3 = \frac{3}{2})$

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

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

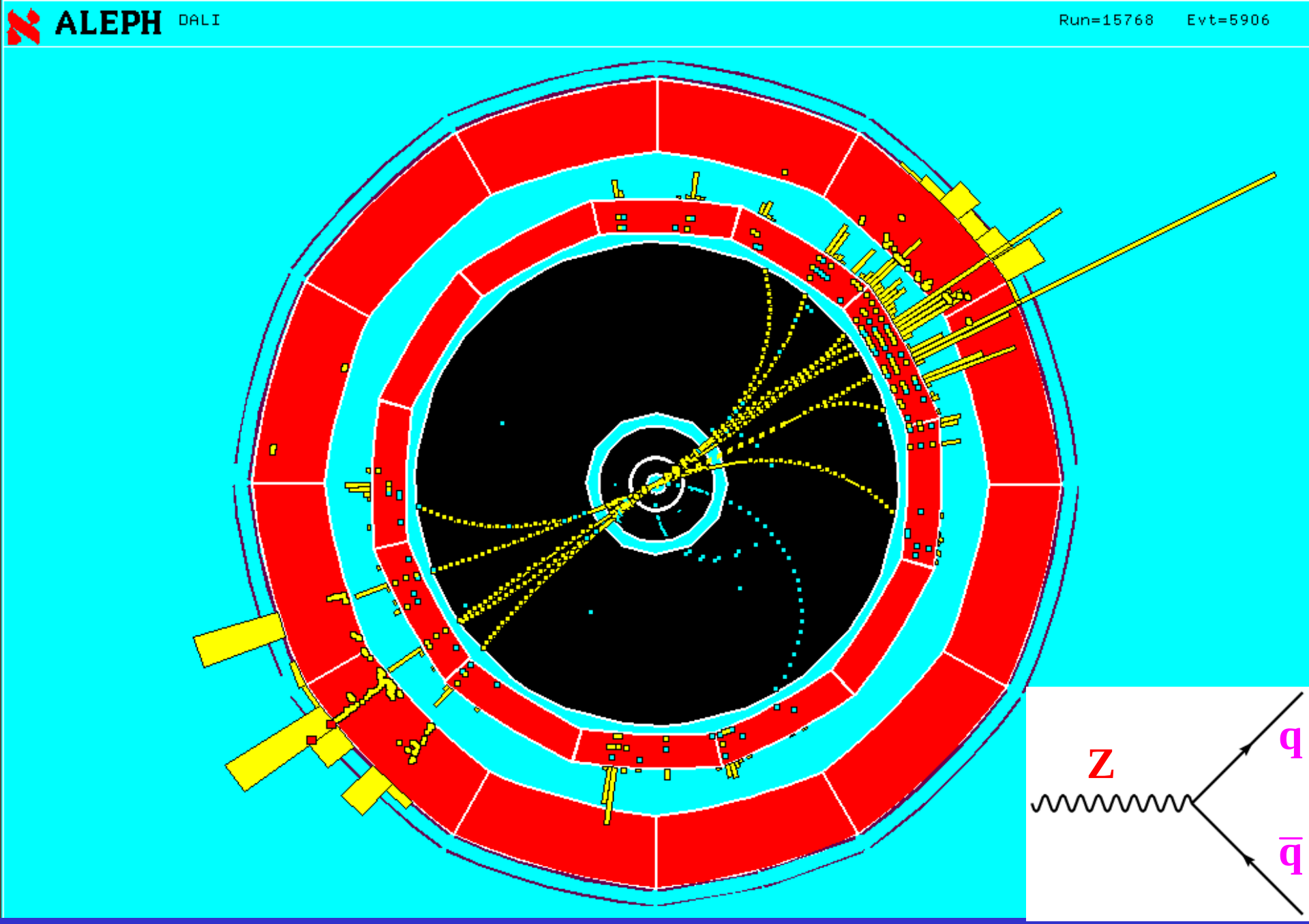
$$N_C = 3 \ \Rightarrow \ q^i\, q^i\, q^i$$

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

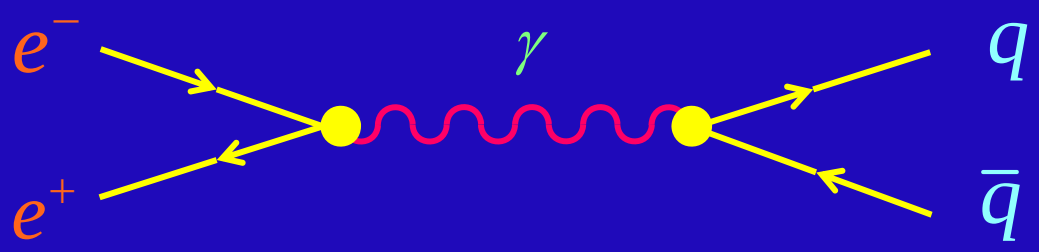
(qqq, $\bar{q}\bar{q}\bar{q}$ and $q\bar{q}$; BUT NOT qq and $qqqq$)

We don´t see Quarks ➡

- Don´t exist ?
- **CONFINEMENT**

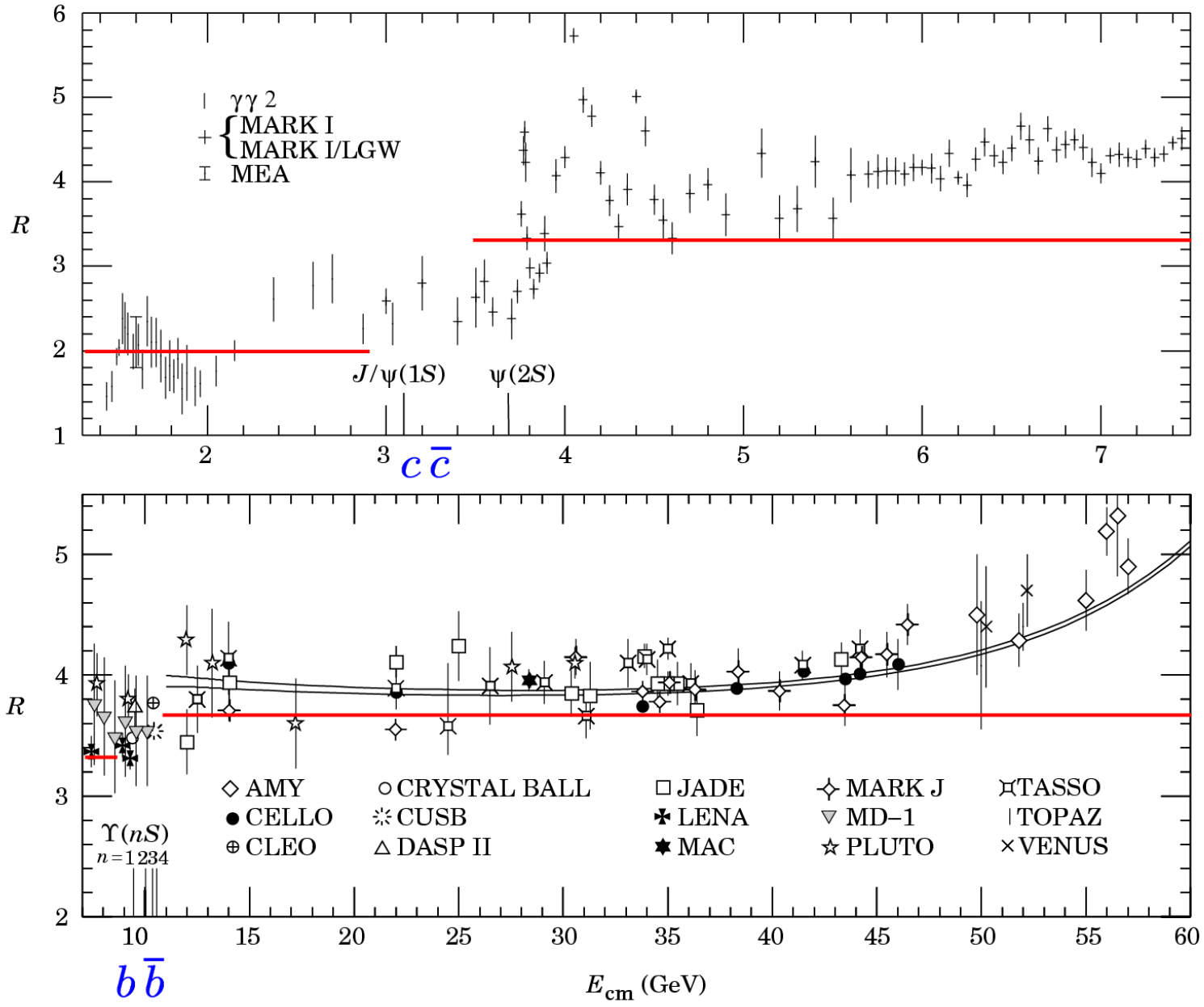

ALEPH
DALI
Run=15768
Evt=5906

Z
q
$\bar{q}$



$$R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} \simeq \frac{\sum_q \sigma(e^+e^- \to q\bar{q})}{\sigma(e^+e^- \to \mu^+\mu^-)} \simeq N_C \sum_q Q_q^2$$

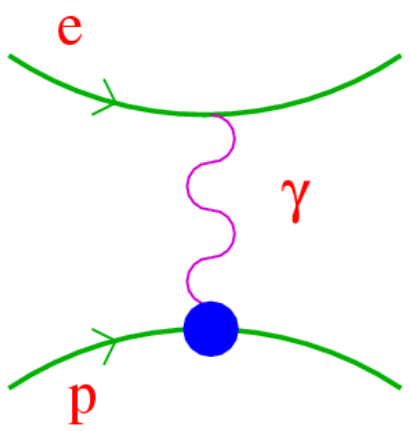
$$= \begin{cases} \frac{2}{3} N_C & , \quad (u,d,s) \\ \frac{10}{9} N_C & , \quad (u,d,s,c) \\ \frac{11}{9} N_C & , \quad (u,d,s,c,b) \end{cases}$$


γγ 2
MARK I
MARK I/LGW
MEA
R
J/ψ(1S)
ψ(2S)
c c̄
Υ(nS)
n=1 2 3 4
AMY
CELLO
CLEO
CRYSTAL BALL
CUSB
DASP II
JADE
LENA
MAC
MARK J
MD–1
PLUTO
TASSO
TOPAZ
VENUS
b b̄
E_cm (GeV)

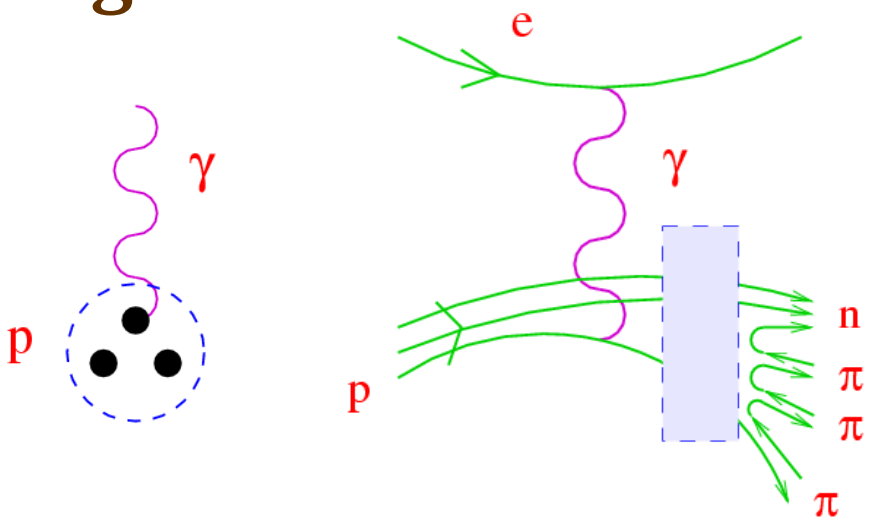
e p Scattering

$\lambda = h / q$

Small E



High E



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

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

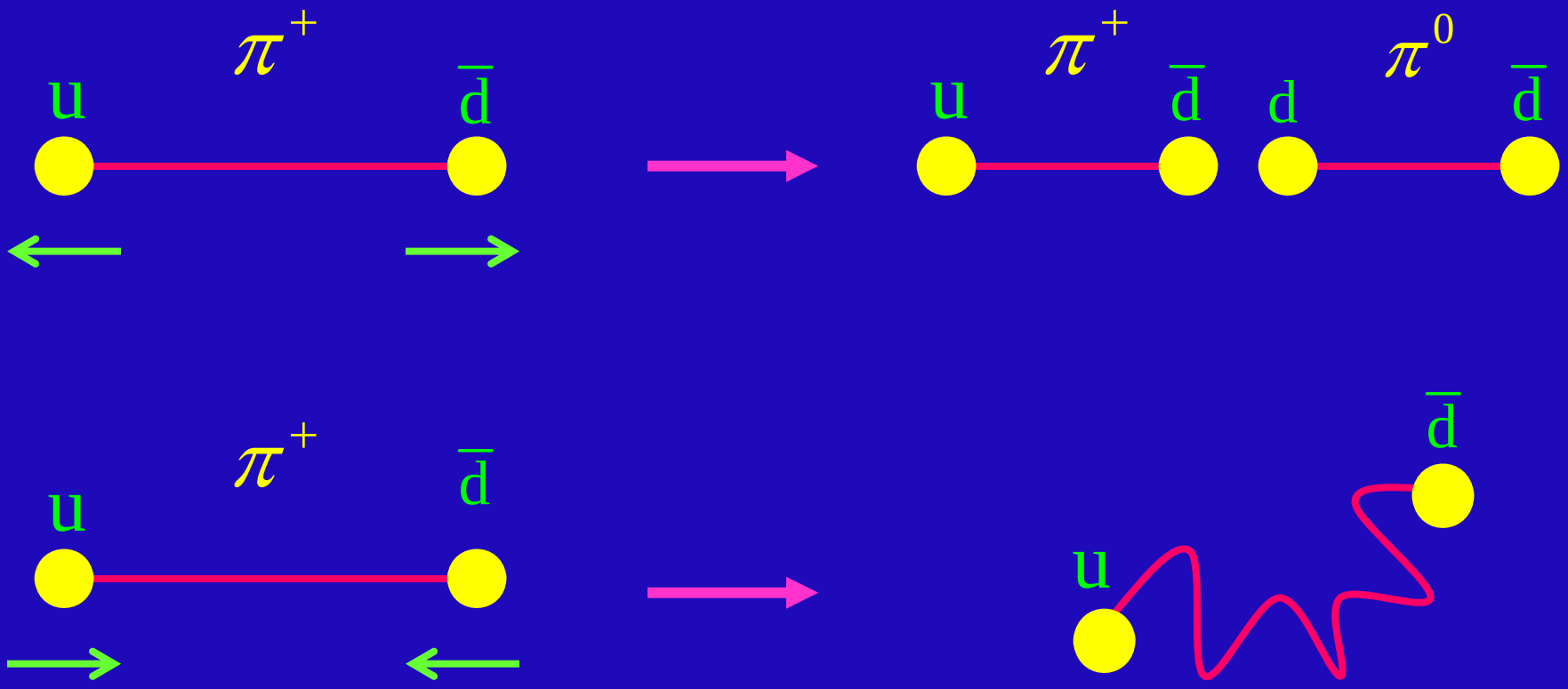
ASYMPTOTIC FREEDOM:

$\alpha_s \to 0$ at large E (short distances)

CONFINEMENT:

Large α_s at small E (large distances)

CONFINEMENT



ASYMPTOTIC FREEDOM

ASYMPTOTIC FREEDOM:

$\alpha_s \to 0$ at large E (short distances)

CONFINEMENT:

Large α_s at small E (large distances)

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

Strong Interactions are { Flavour Independent; Flavour Conserving } COLOUR DYNAMICS

Weak Interactions change the Quark Flavour: FLAVOUR DYNAMICS

Quarks

up

down

charm

strange

top

beauty

Leptons

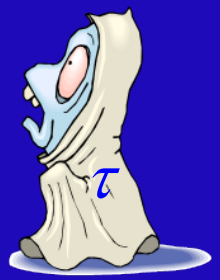
electron

neutrino e

muon

neutrino μ

tau



neutrino τ

Bosons

photon

gluon

Z^0 $W^{\pm}$

Higgs