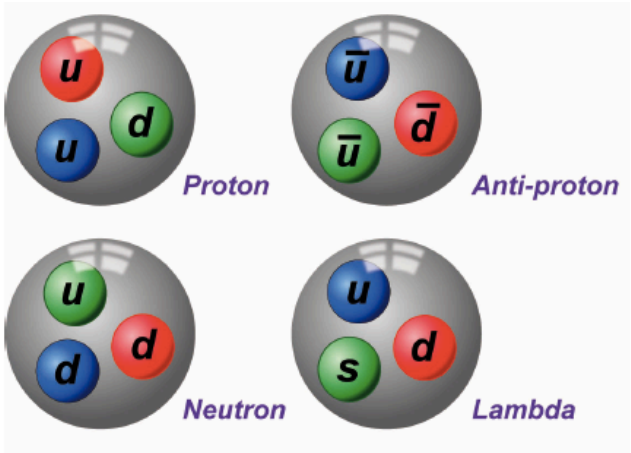
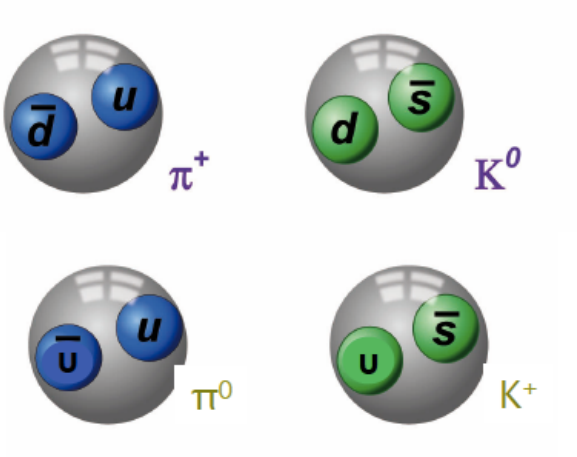
The strong interaction

Quarks

baryons



mesons



and color

From ~ 1940's to 1960's discovery of a lot of particles

→ The quarks model of Gell-Mann and Zweig (1962) :

Hadrons are composite states of more fundamental degrees of freedom : the quarks

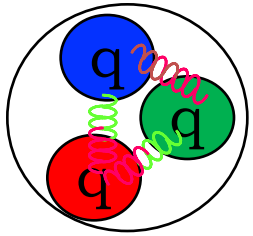
→ Quarks properties :

Reductionist approach
Use of symmetries (similar masses)

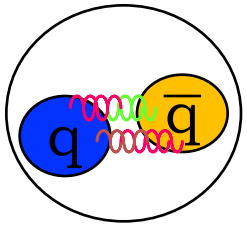
- Spin ½
- Fractional electric charges : +2/3 or -1/3
- Quarks have a new quantum number : color and $N_c = 3$
- SU(3) symmetry
- Hadrons are color singlets

What was needed :

Q= 2/3	u, Mass ~ few MeV	
Q= -1/3	d, Mass ~ few MeV	s, Mass ~ few hundred MeV

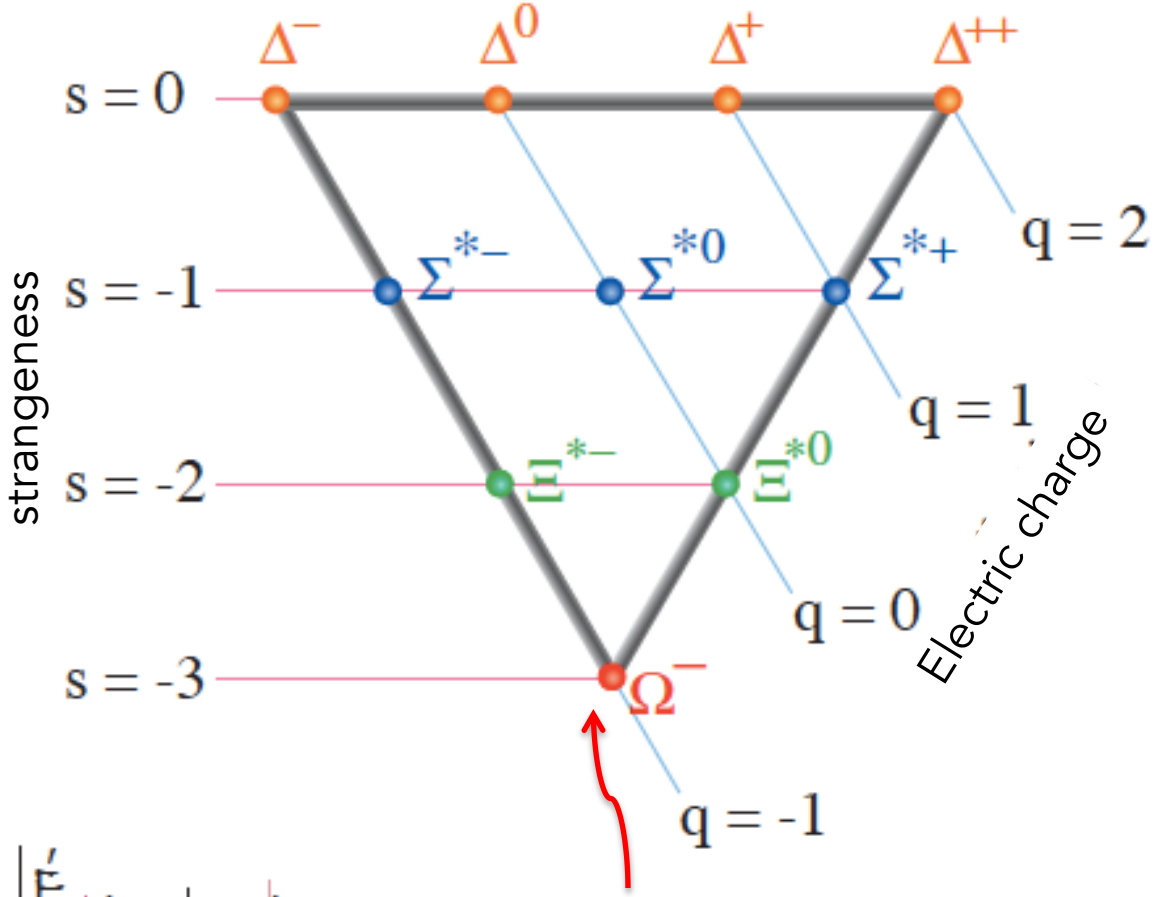


Baryons : spin ½ or 3/2



Mesons: spin 0 or 1

A whole zoo of particles can be classified …
Building of the baryons (3 quarks)



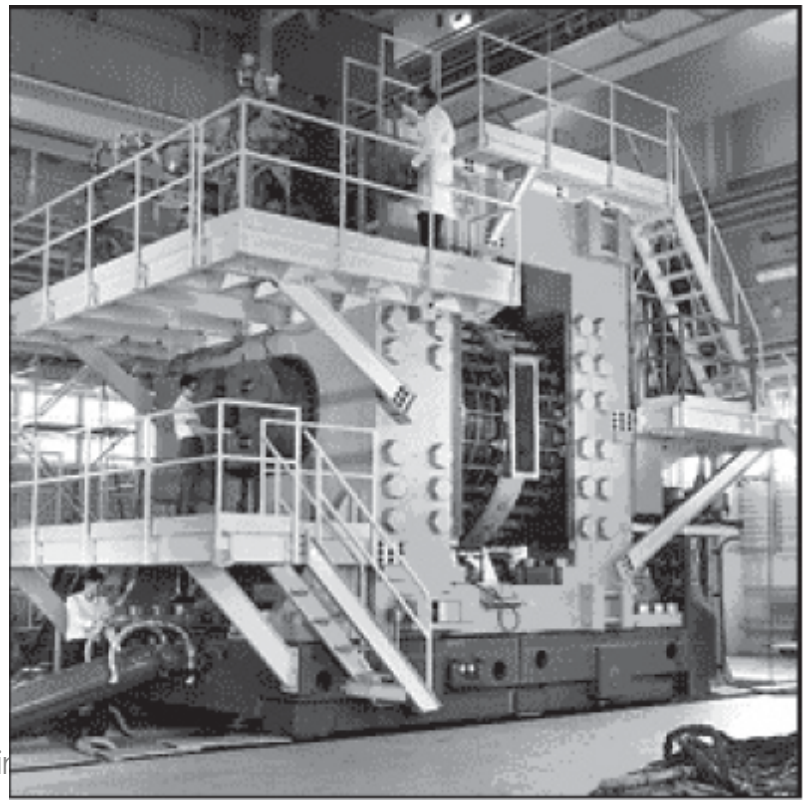
	Mass	Discovery year
Δ^{-} Δ^{0} Δ^{+} Δ^{++}	~ 1.232 GeV	(1950-60)
Σ^{*-} Σ^{*0} Σ^{*+}	~ 1.385 GeV	(1961)
Ξ^{*-} Ξ^{*0}	~ 1.533 GeV	(1962)
Ω^{-}	~ 1.686 GeV	(1963)

Some particles can be predicted

In 1962 Ne'eman and Gellman predicted the existence of a (sss) baryon

ICHEP @ CERN (1962)

Brookhaven bubble chamber, 80000 pictures !



1000 liters of liquid Hydrogen

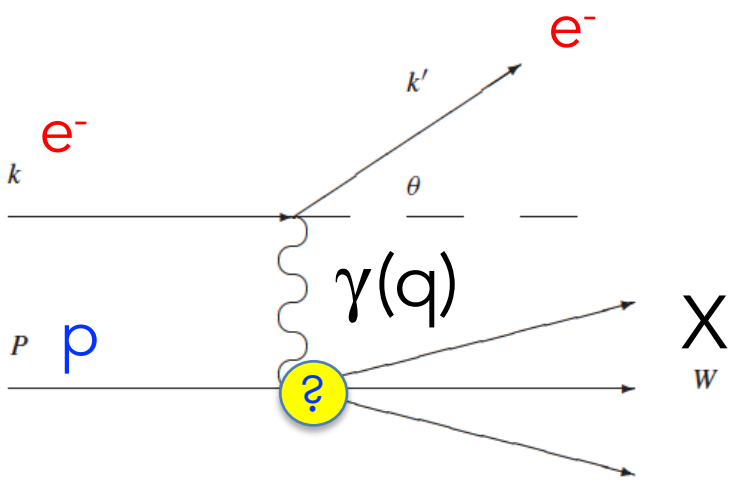
But are those quarks just artificial mathematical concepts or are they real ?

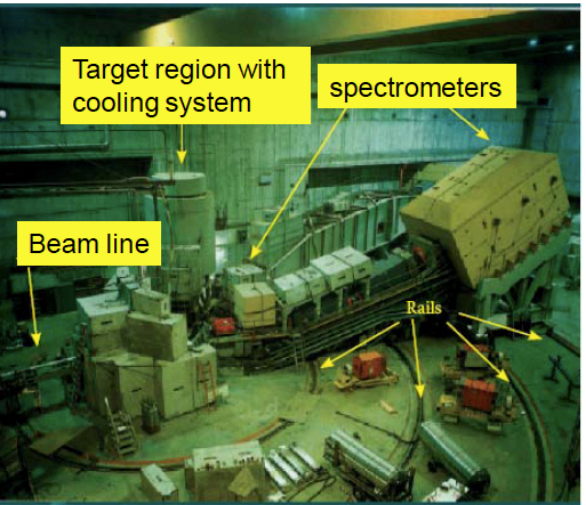
Deep Inelastic Scattering (DIS)

$e^- p \rightarrow e^- X$ (X=p,n,π,..)

$Q^2 = -q^2$

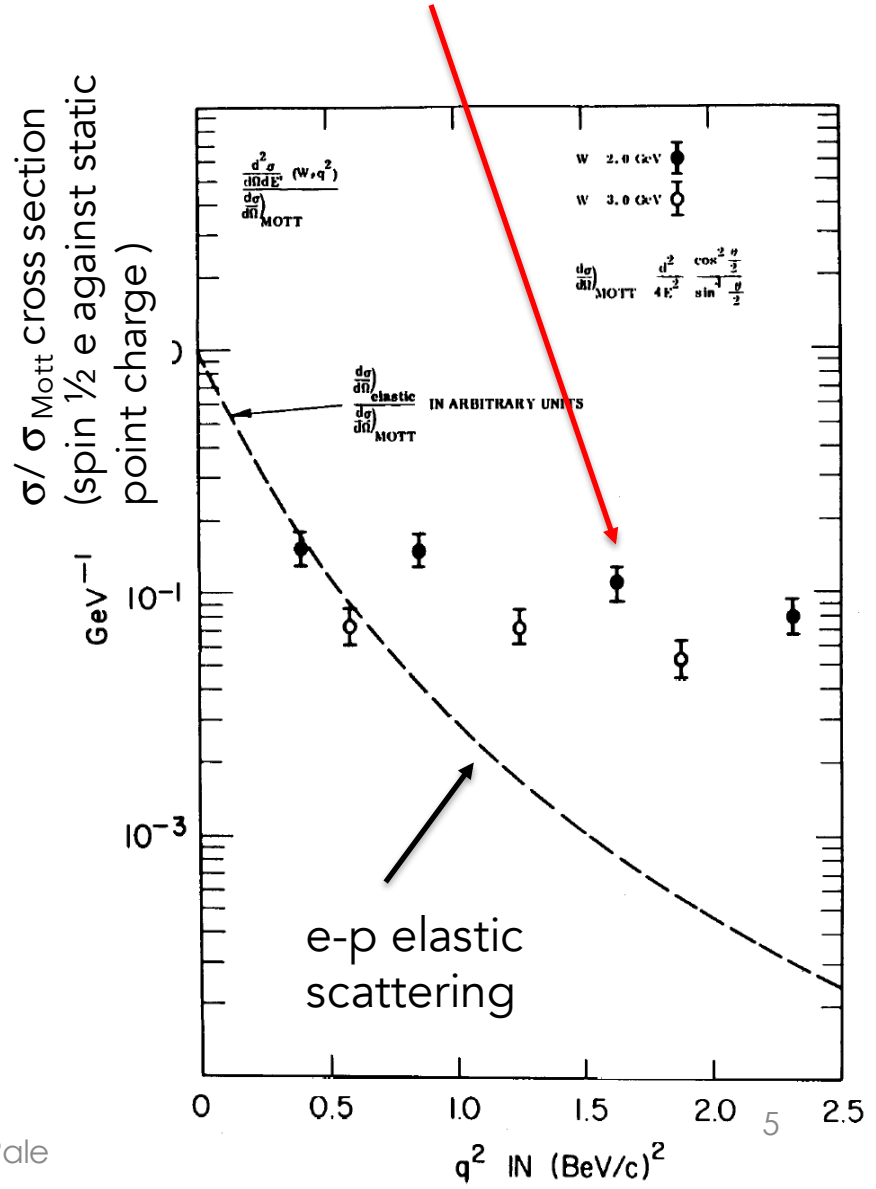
$W^2 = M_X^2 = (p_p + q)^2$



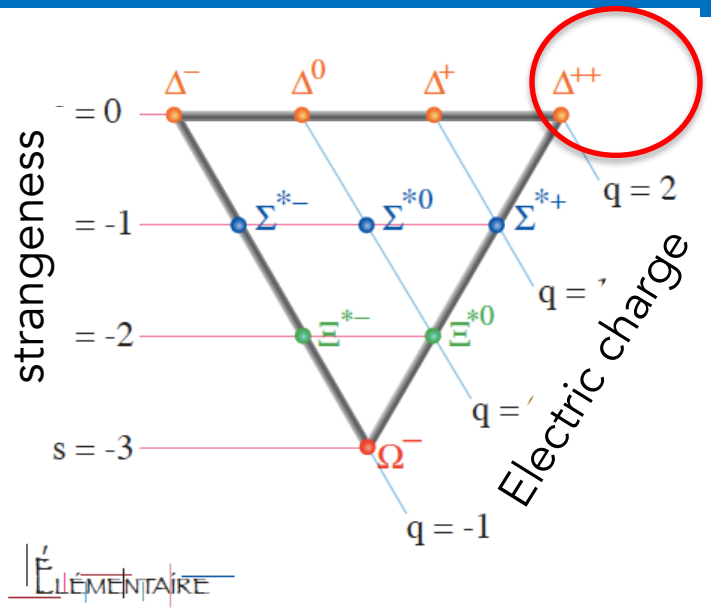


SLAC 1969

Evidence for internal substructure: weak decrease with q^2



QCD : the color



3 identical quarks all spin up

Pauli exclusion principle

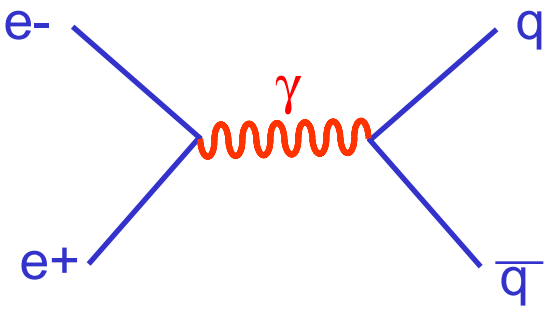
→ color

$\Delta^{++} \qquad |u_R \uparrow u_B \uparrow u_G \uparrow\rangle \qquad J^P = 3/2^+$

→ SU(3)

- charge for the strong interaction : colour charge
- SU(3) :3^2-1 = 8 generators ⇒ 8 gluons vector particles of the strong interaction
- quarks carry a colour charge (R, G or B)
- the colour exchange takes place through 8 bicoloured gluons

Experimental evidence : the R ratio



$$R = \frac{\sigma(e^+e^- \rightarrow hadrons)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = N_c \sum_i q_i^2$$

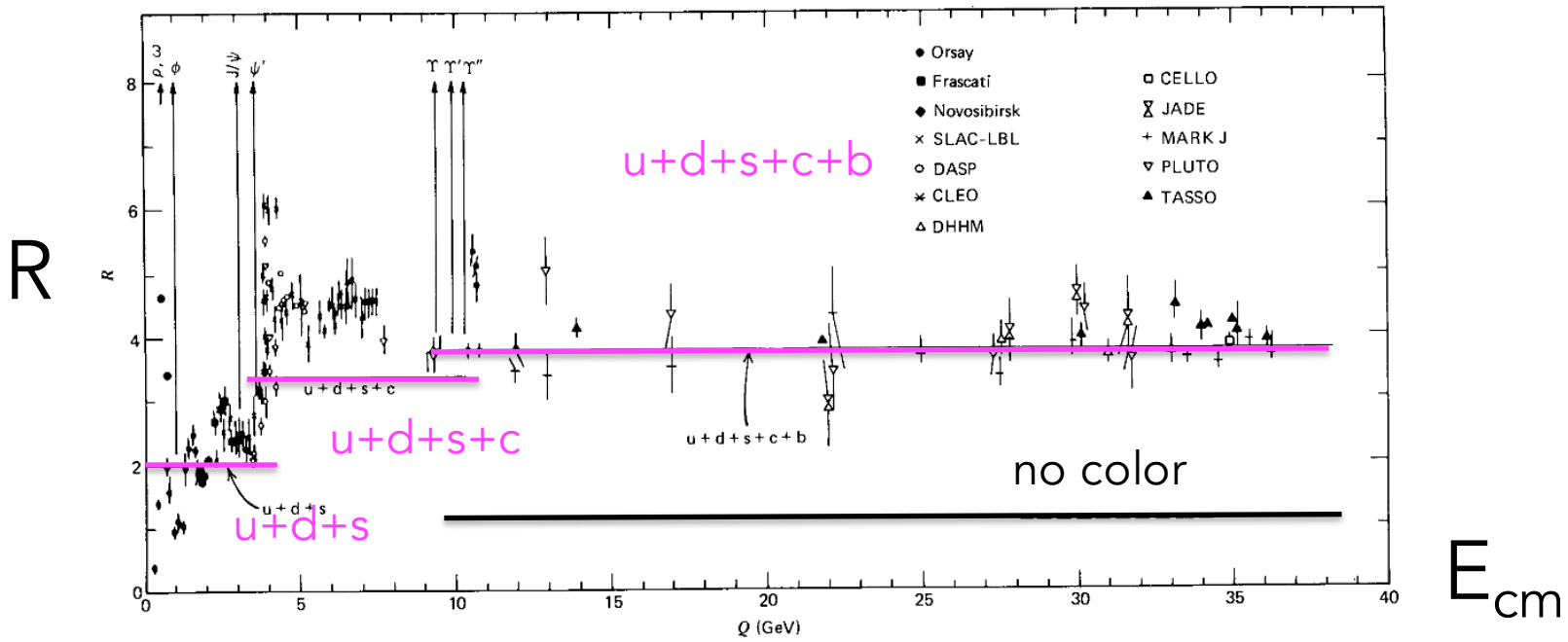
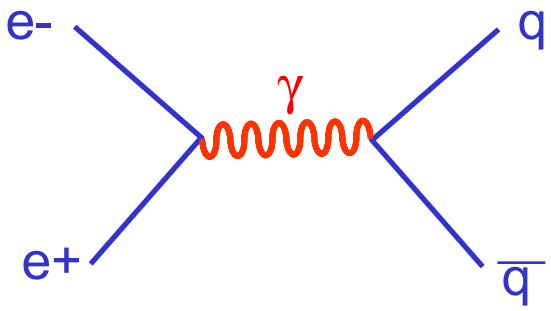


Fig. 11.3 Ratio R of (11.6) as a function of the total e^-e^+ center-of-mass energy. (The sharp peaks correspond to the production of narrow 1^- resonances just below or near the flavor thresholds.)

Experimental evidence : the R ratio



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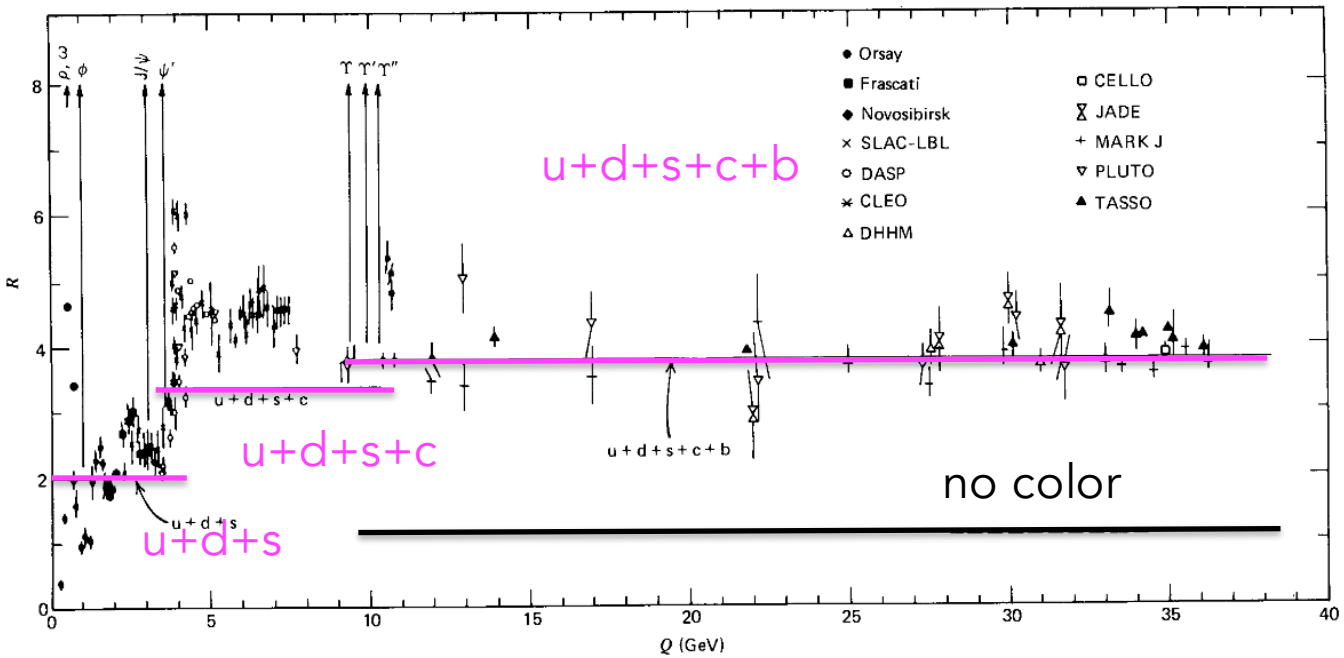
R

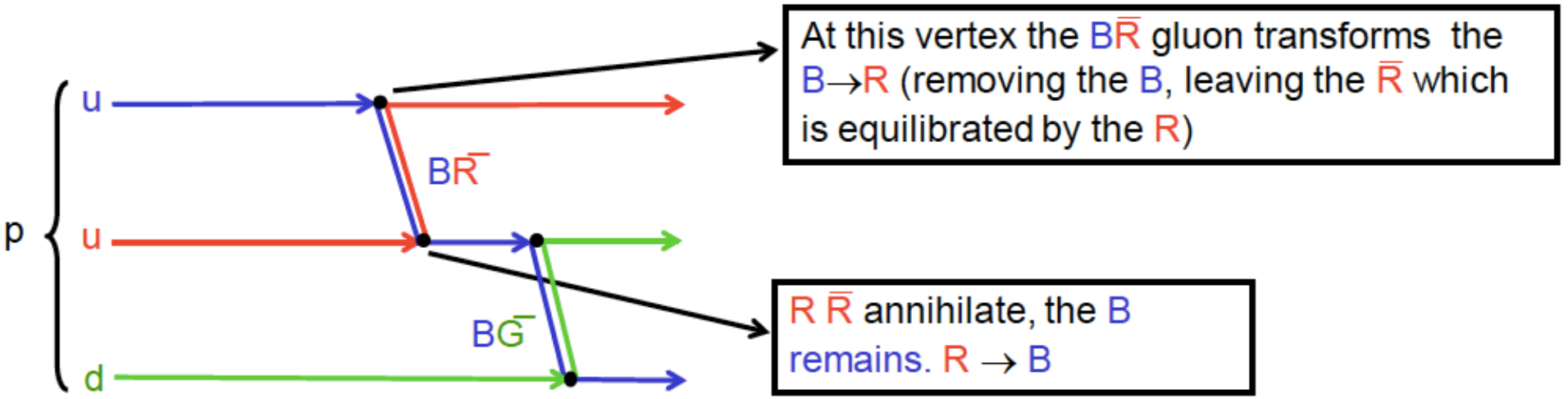


E_{cm}

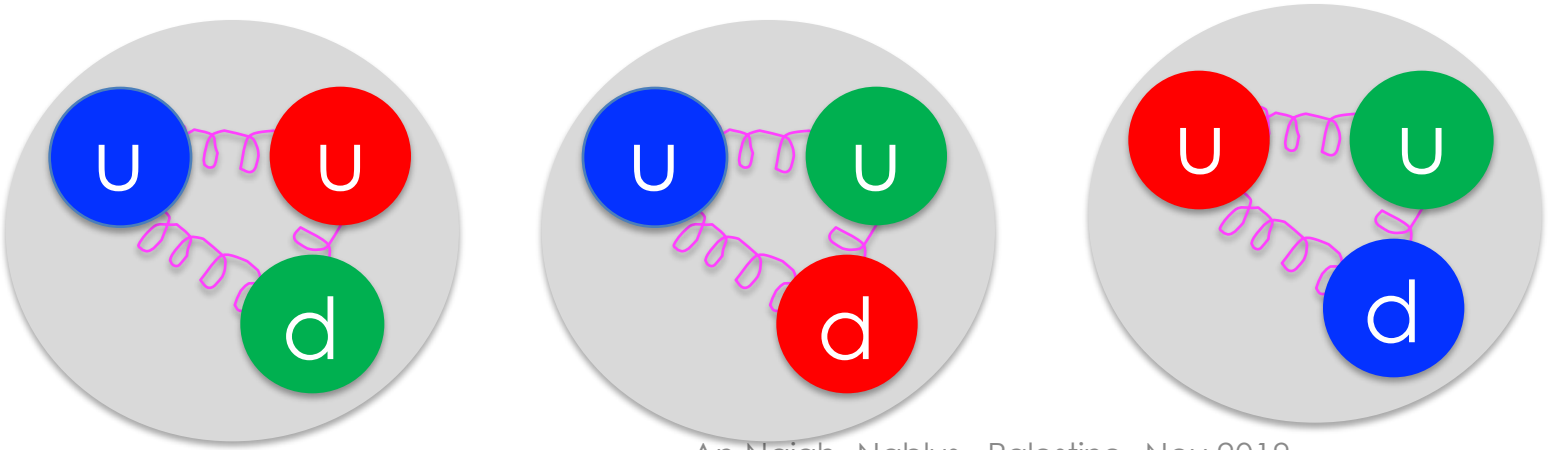
Fig. 11.3 Ratio R of (11.6) as a function of the total e^-e^+ center-of-mass energy. (The sharp peaks correspond to the production of narrow 1^- resonances just below or near the flavor thresholds.)

QCD is the theory based on colour-SU(3) which describes the strong interaction :

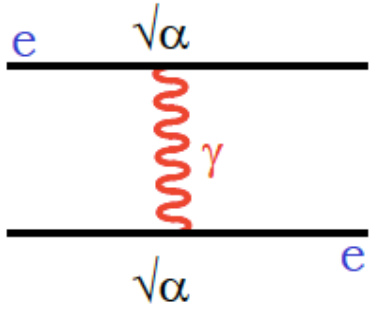
Proton description :



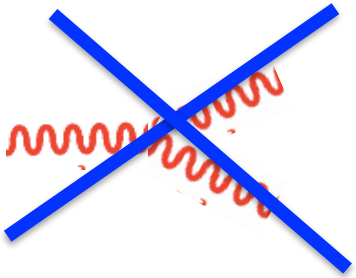
The proton is a mixture of : $u_R u_B d_G$, $u_R u_G d_B$, $u_B u_G d_R$, ….



QED :

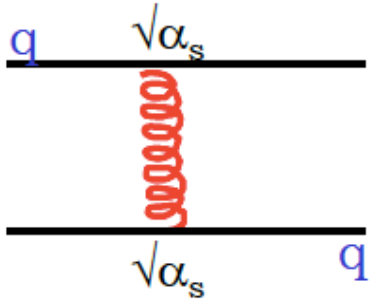


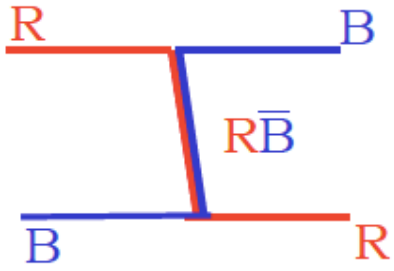
1 photon :
- massless
- electrically neutral



Does not exist

QCD :





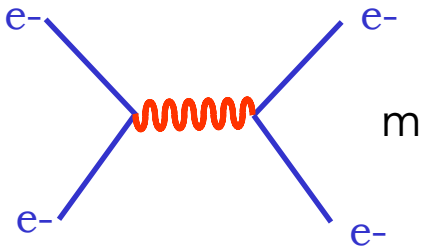
8 gluons :
- massless
- colored

gluon self-interaction

!

QED :

$$\alpha(Q^2) = \frac{\alpha(\mu^2)}{1 + \frac{\alpha(\mu^2)}{4\pi}\left(-\frac{4}{3}\right) log\left(\frac{Q^2}{\mu^2}\right)}$$



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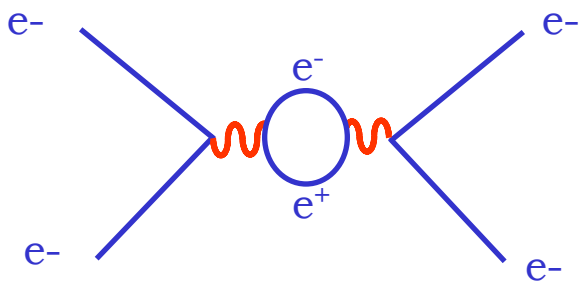
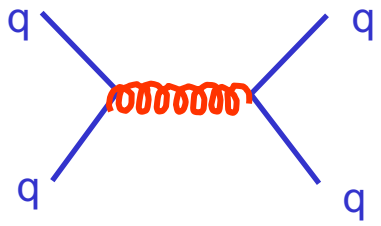


QCD :

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \frac{\alpha_s(\mu^2)}{4\pi}\left(-\frac{2n_f}{3} + 11\right) log\left(\frac{Q^2}{\mu^2}\right)}$$



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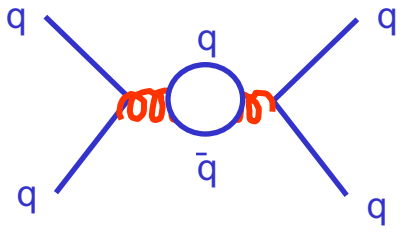

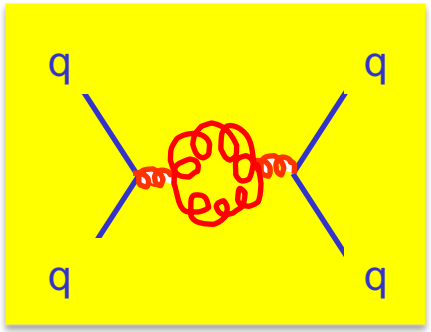

n_f : number of flavours

In the SM $\left(-\frac{2n_f}{3} + 11\right) > 0$

QED :

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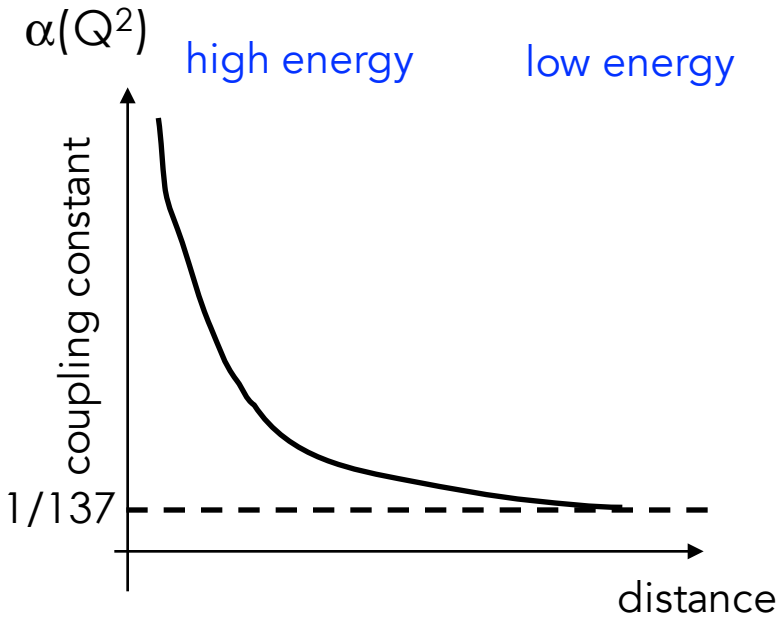

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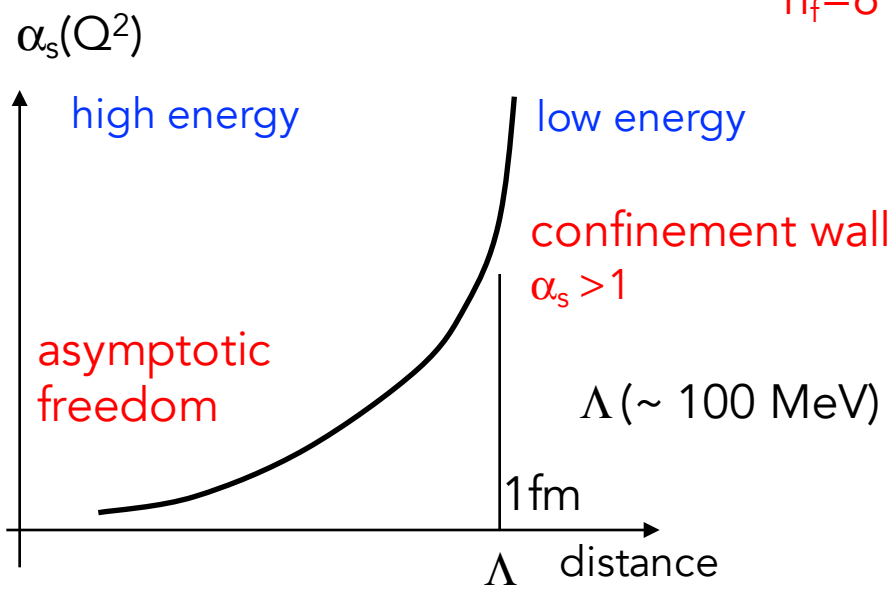
n_f=6



$Q^2 \sim \Lambda^2$ strong coupling ~~perturbations~~

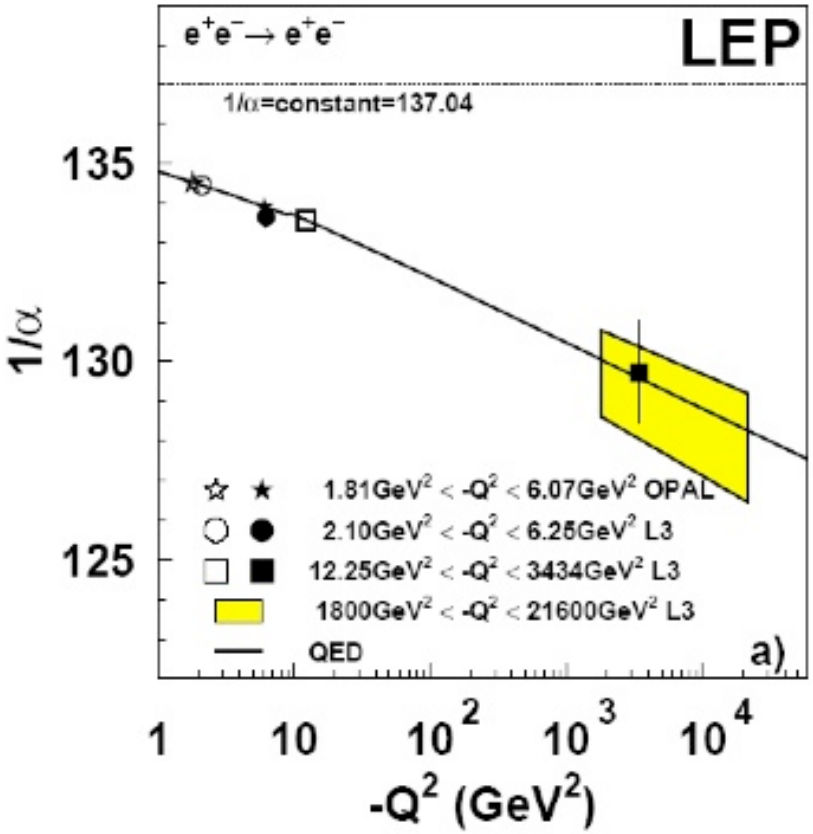
$Q^2 >> \Lambda^2$ weak coupling perturbations

non intuitive!

Colour confinement

QED :

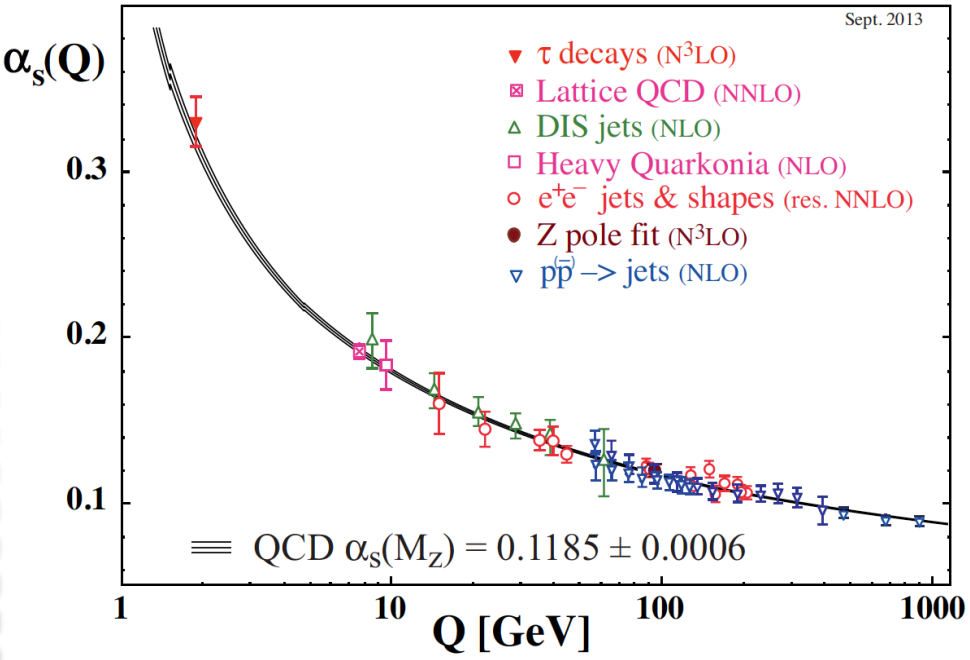
Evolution of $1/\alpha$ as a function of E



When the energy increases (the distance decreases) α increases

QCD :

Evolution of α_s as a function of E



When the energy increases (the distance decreases) α_s decreases

Strong interaction in summary

- 3 charges (Red Blue Green)
- Strong interaction coupling (α_s) is universal
- The vector boson of QCD carries color
  - free quarks are not observed
  - mesons and baryons (… and more !)
  - asymptotic freedom
  - no perturbation theory building possible at low energy → models to be developed