A short introduction to the strong interaction

… Quarks, gluons and their interaction

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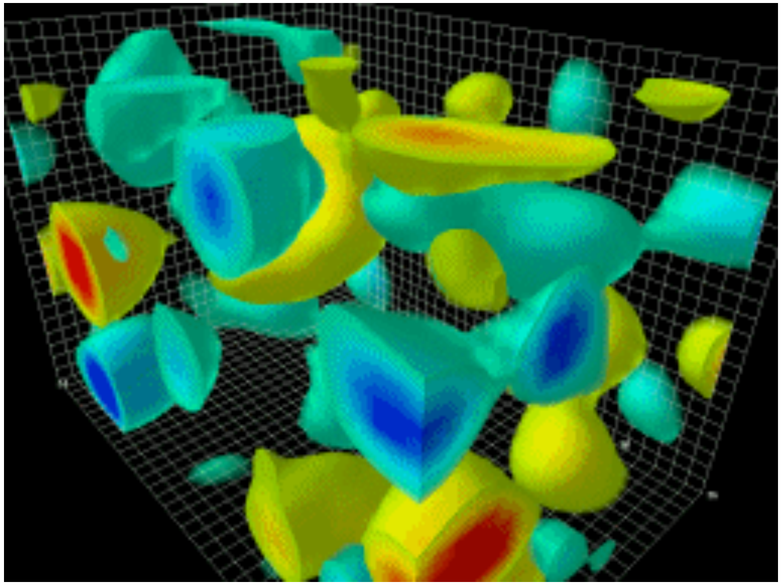


- Historical approach
  - Strong isospin SU(2)
  - Strangeness and SU(3)

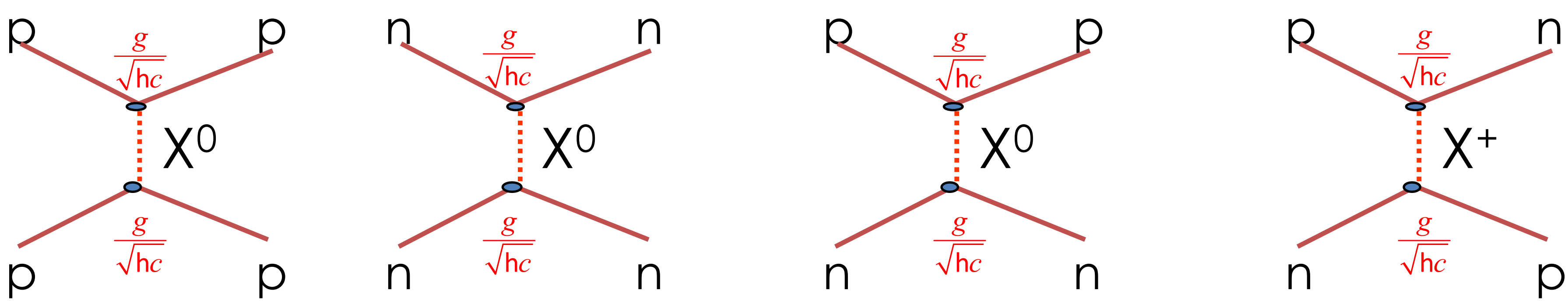
- The quarks model

- Color and QCD

Historical approach

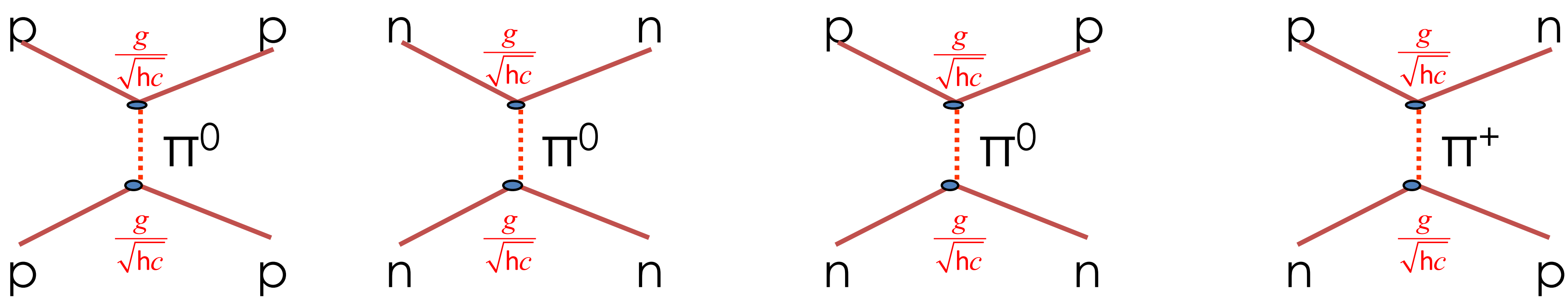
In the 30's : Study of the p-n p-p and n-n scattering

$\sigma_{strong} \sim 10^{-30}\,m^2$ $\sigma_{elm} \sim 10^{-36}\,m^2$ $\sigma_{weak} \sim 10^{-42}\,m^2$

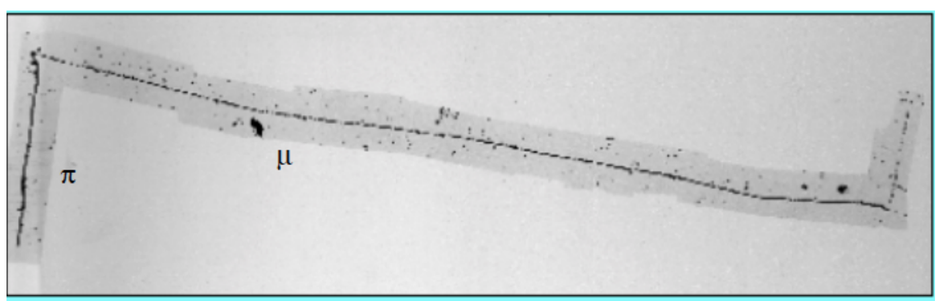


Heisenberg principle : $\Delta t \approx \frac{\hbar}{\Delta E} = \frac{\hbar}{mc^2}$ $R = \frac{\hbar c}{mc^2}$ *($R = c\,\Delta t$)*

Yukawa (1934) : range ~ 1 fm → exchange of particles with a mass ~200 MeV



Experimentally : strong interaction does not depend on the electric charge (same intensity for np, nn and pp reactions) → X exchange of same mass



(Charged) pion meson discovered in cosmic rays in 1947

The strong isospin :

The n-p system from the strong interaction point of view :

The electric charge is conserved

The n-p interactions do not depend on the electric charge

$M(n) \sim M(p)$

For the strong interaction n = p

→ The strong interaction is invariant under the symmetry which exchanges n and p which is of type SU(2)

→ 3 generators : the Pauli matrices σ_i $\quad \sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

Remember spin ½ algebra ?

$$|n\rangle \quad |p\rangle \qquad \begin{pmatrix}0\\1\end{pmatrix} \quad \begin{pmatrix}1\\0\end{pmatrix} \qquad \begin{cases} I_+|n\rangle = |p\rangle \\ I_-|p\rangle = |n\rangle \end{cases} \quad \text{and} \quad \begin{cases} I_+|p\rangle = 0 \\ I_-|n\rangle = 0 \end{cases}$$

$$Q = \begin{pmatrix}1 & 0\\0 & 0\end{pmatrix} \qquad Q = \tfrac{1}{2}(\underbrace{\sigma_3}_{I_3} + \mathbf{1}) \qquad I_+ = \frac{1}{2}(\sigma_1 + i\sigma_2) \quad I_- = \frac{1}{2}(\sigma_1 - i\sigma_2)$$

The electric charge is conserved

$$\Leftrightarrow [H_F,\sigma_3] = [H_F,I_3] = 0$$

The n-p interactions do not depend on the electric charge

$$[H_F, I_\pm] = 0 \qquad \Rightarrow [H_F, I_1] = [H_F, I_2] = [H_F, I^2] = 0$$

$$[H_F, \sigma_i] = 0 \qquad i = 1,2,3$$

And one gets …

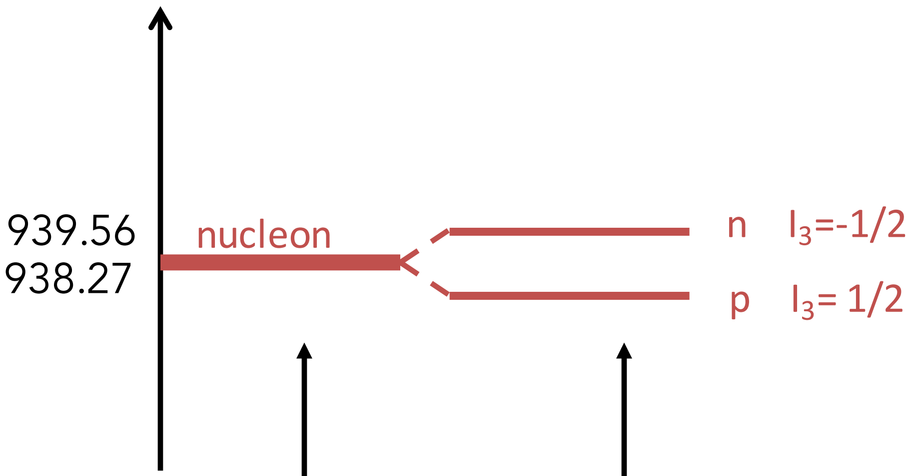
$$I_+|n\rangle = |p\rangle \quad \Rightarrow HI_+|n\rangle = H|p\rangle \quad \Rightarrow I_+H|n\rangle = H|p\rangle$$

$$\Rightarrow m_n I_+|n\rangle = m_p|p\rangle \quad \Rightarrow m_n|p\rangle = m_p|p\rangle$$

$$\Rightarrow m_n = m_p$$

$\boxed{H|p\rangle = m_p\,|p\rangle}$

Sketch of the symmetry :



The electromagnetic interaction

- depends on electric charge

  $n \neq p \Rightarrow [H_{elm}, I_\pm] \neq 0$

- conserves the electric charge

  $[H_{elm}, I_3] = 0$

$H_{int} = H_{Strong} + H_{elm}$

invariant under SU(2)-isospin

(partially) broken SU(2)-isospin

$[H_{Strong}, I_\pm] = [H_{Strong}, I_3] = 0$

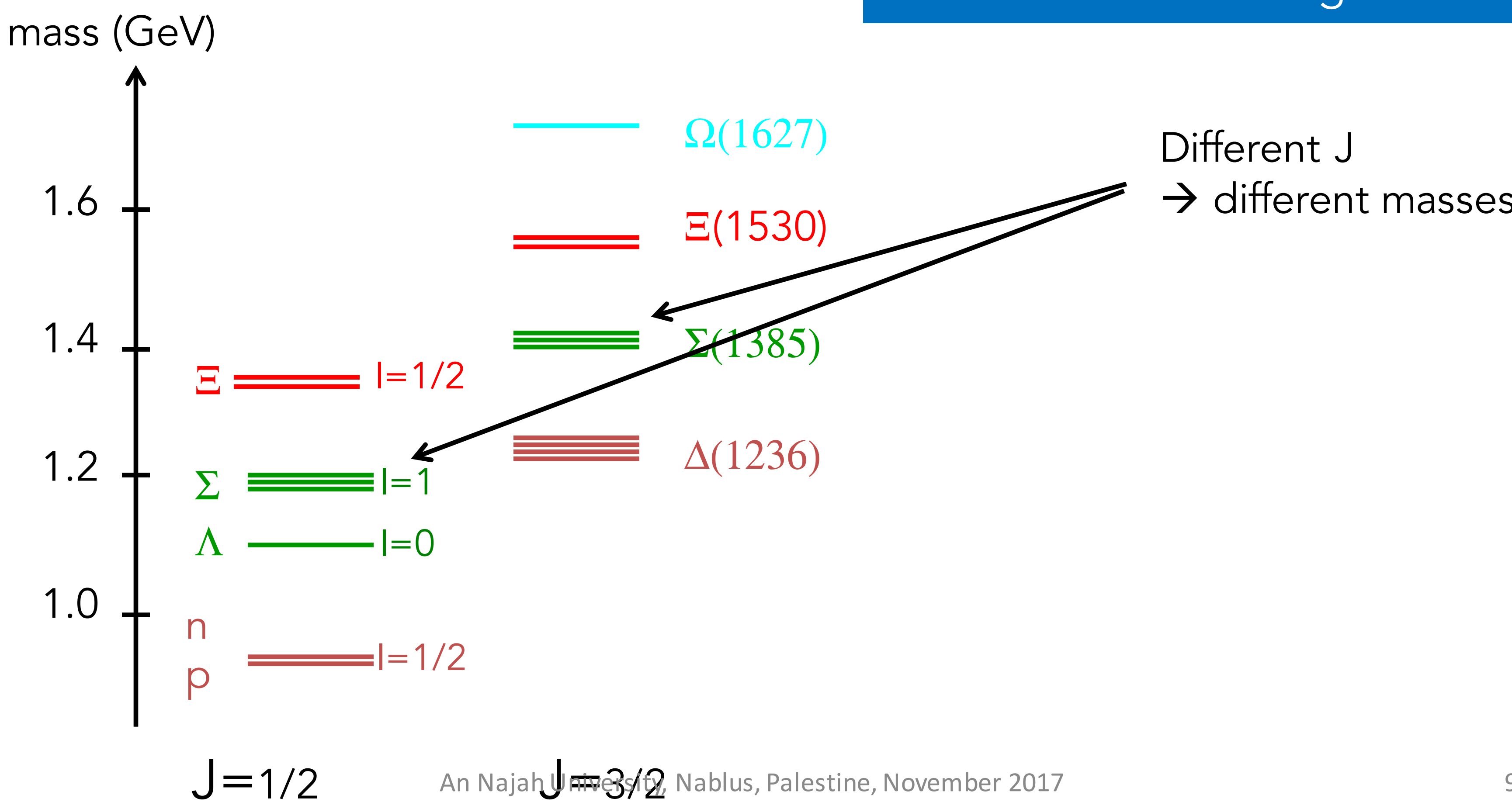
→ Isospin multiplets

- Experimental : isospin conservation in π-N interactions

  $\Rightarrow$ (π^+ π^- π^0) isospin 1

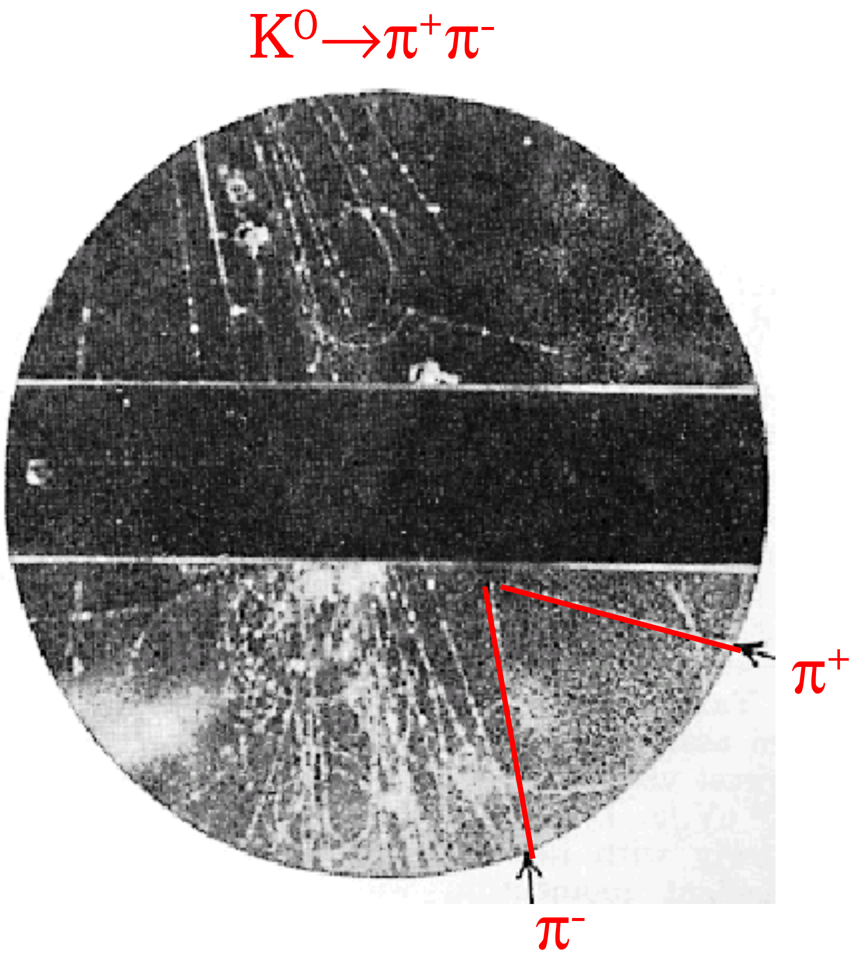
- Isospin multiplets :

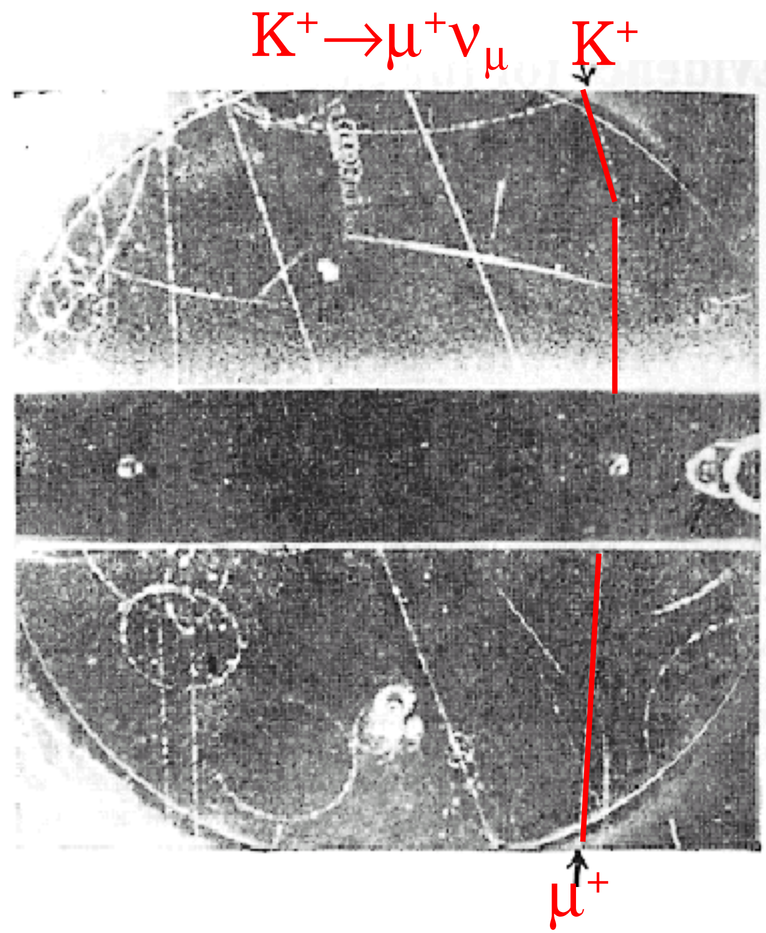
multiplets : «groups» of particles with same quantum numbers (spin parity), similar masses but different electric charges



An other experimental observation : the discovery of the 'strange' particles

- 1947 observation of cosmic rays in a cloud chamber
  - K (~500 MeV) Λ(~1100 MeV)

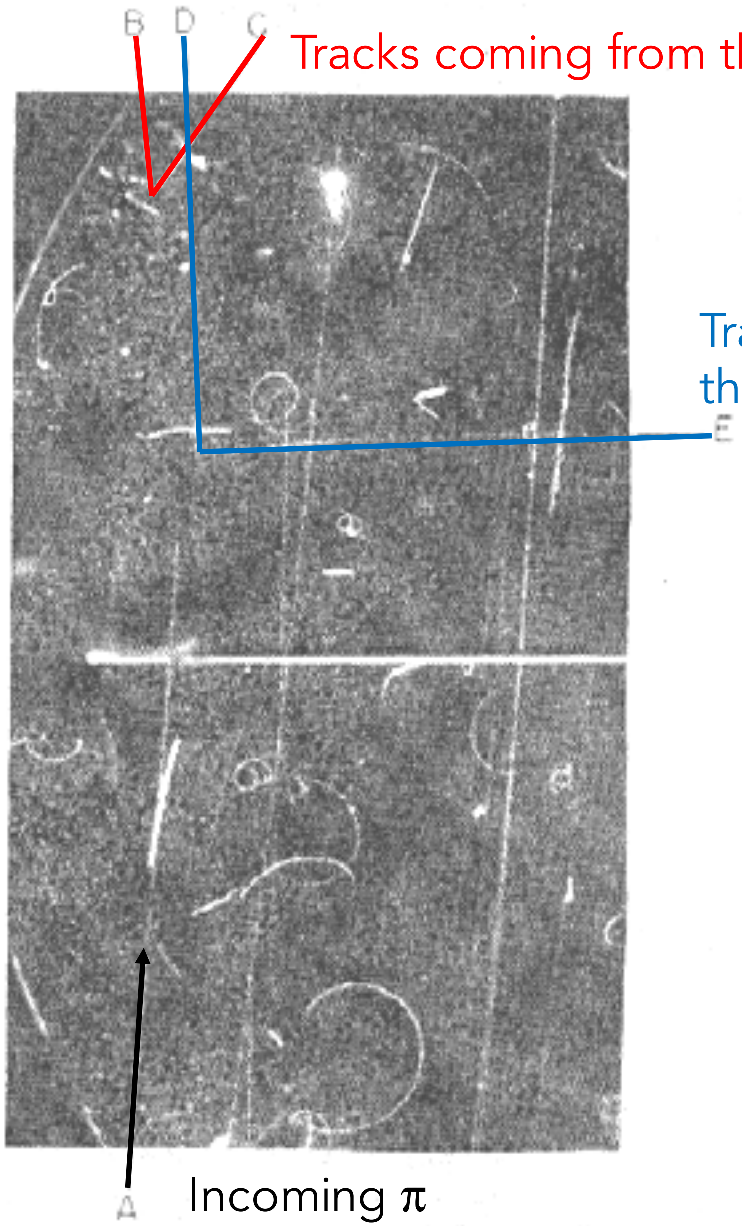




V-particle

«Kink» in the detector

1955 Walker *et al*
(Berkeley)



$$\pi^- p \to K^0 \Lambda^0$$

Pair production

FIG. 1. $\Lambda^0-\theta^0$ production in a $\pi^- - P$ collision. Track A is the incoming π^- meson which disappears in flight. Direct measurements on this track give a momentum between 1.05 and 1.3 Bev/c. The adjacent π^- meson which crosses the chamber has a momentum of 1.14±0.10 Bev/c. Tracks B and C are the decay products of a Λ^0. Track C is short but momentum measurements give a momentum of less than 100 Mev/c and a negative sign. Tracks D and E are the π^- and π^+ mesons from the decay of the θ^0. Measurements on the π^+ meson give 153±8 Mev/c for the momentum.

- Why strange ?
  - Cross section of the production ~ to that of the π
  - Produced by pair
  - Lifetime ~10^{-10} s ! (not the scale of the strong interaction ~ 10^{-23} s)
- They are produced by the strong interaction but decay via another one
- What forbids the strong interaction in the decay ?

Pais (1952) :
New quantum number
conserved by the strong interaction
non conserved by the weak interaction

→ The strangeness

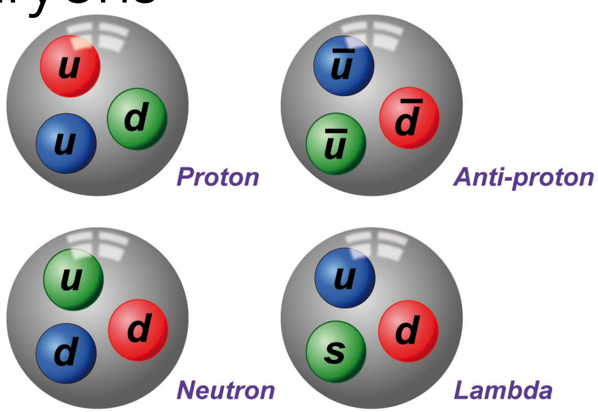
We would like to be able to describe the full zoo of hadrons

π but also Λ Δ Ξ Σ ….. Neutral and charged !

→ the quarks model *Gell-Mann Zweig 1962*

$$q_1 q_2 q_3 \;, \quad \bar{q}_1 \bar{q}_2 \bar{q}_3 \;, \quad q_1 \bar{q}_2$$

baryons



…

mesons

…

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Reductionist approach, use of symmetries (similar masses)

The quarks model

The quarks model of Gell-Mann and Zweig :

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

→ Quarks properties :

- 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

Let's start with 2 quarks

$$|u\rangle, |d\rangle$$

Remember 2 spin ½ combination ?

- The mesons are composed of $q_1\ \bar{q}_2$
- With u and d only it is similar to spin ½ composition
- One gets:

1 triplet

$$|I=1, I_3=1\rangle = u\bar{d}$$

$$|I=1, I_3=0\rangle = \sqrt{1/2}\left(u\bar{u}-d\bar{d}\right)$$

$$|I=1, I_3=-1\rangle = d\bar{u}$$

1 singlet

$$|I=0, I_3=0\rangle = \sqrt{1/2}\left(u\bar{u}+d\bar{d}\right)$$

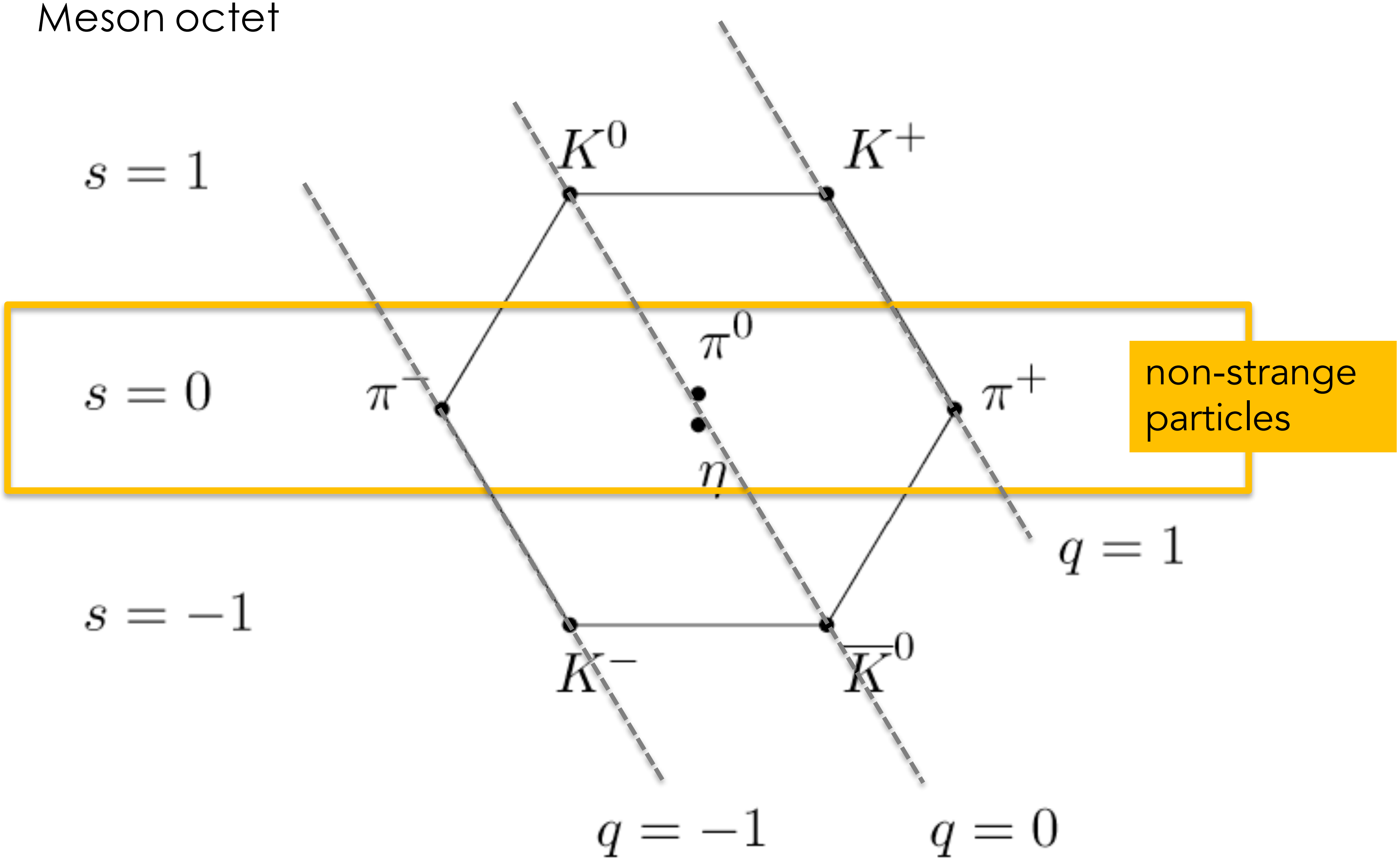
π+
π0 3(A)
π-
η 1(S)

Known particles

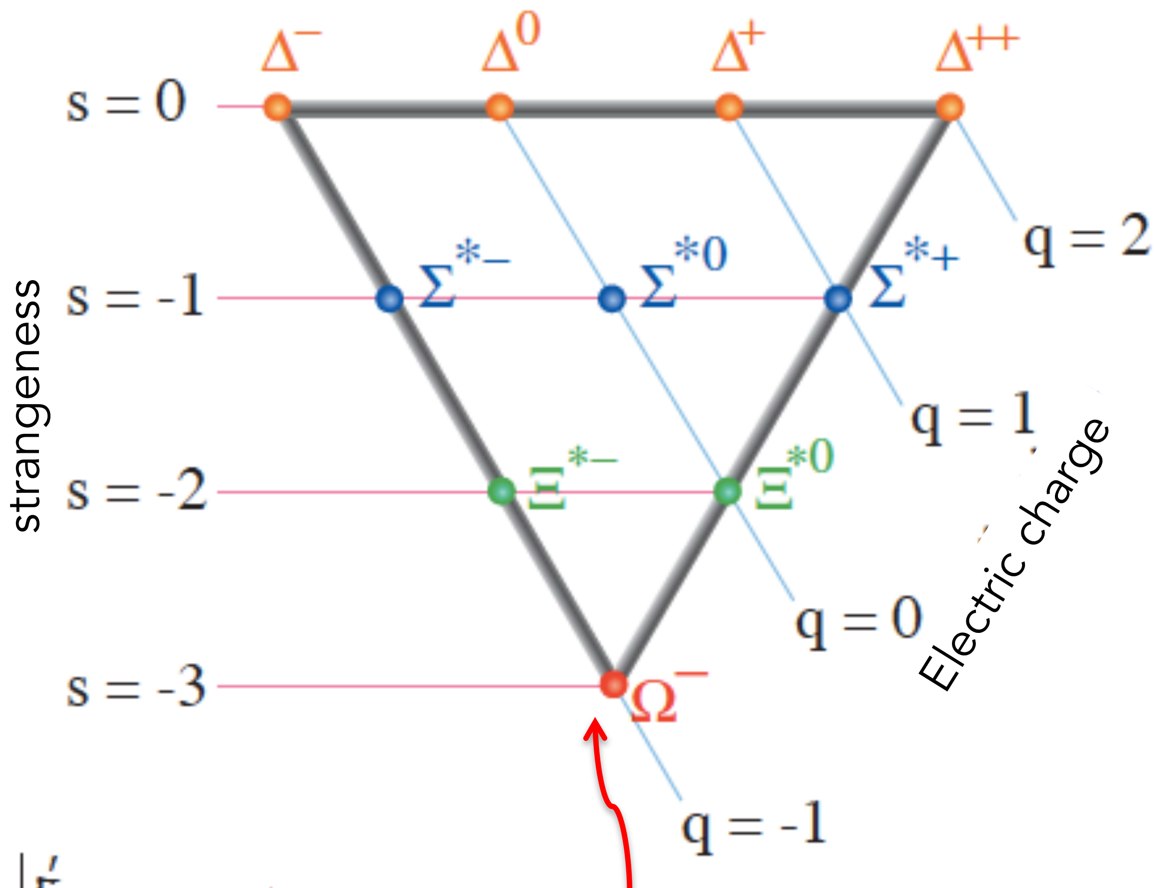
But in fact one needs also to take into account the strange quark …

SU(2) → SU(3)

Meson octet



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



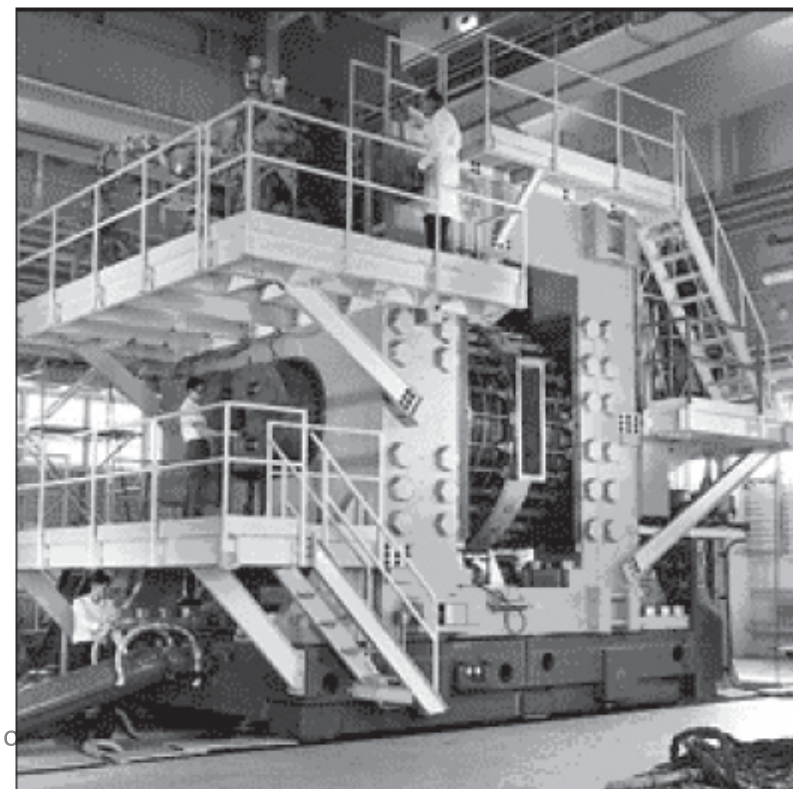
Mass	Discovery year
~ 1.232 GeV	(1950-60)
~ 1.385 GeV	(1961)
~ 1.533 GeV	(1962)
~ 1.686 GeV	(1963)

Some particles can be predicted

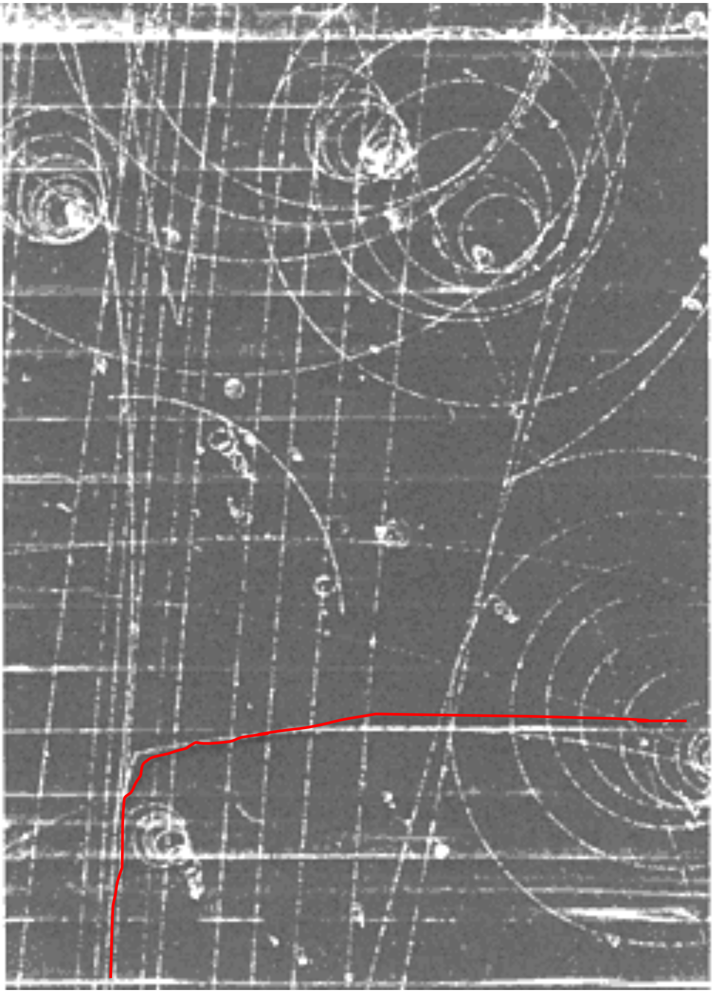
In 1962 Ne'eman and Gellman predicted the existence of a (sss) baryon

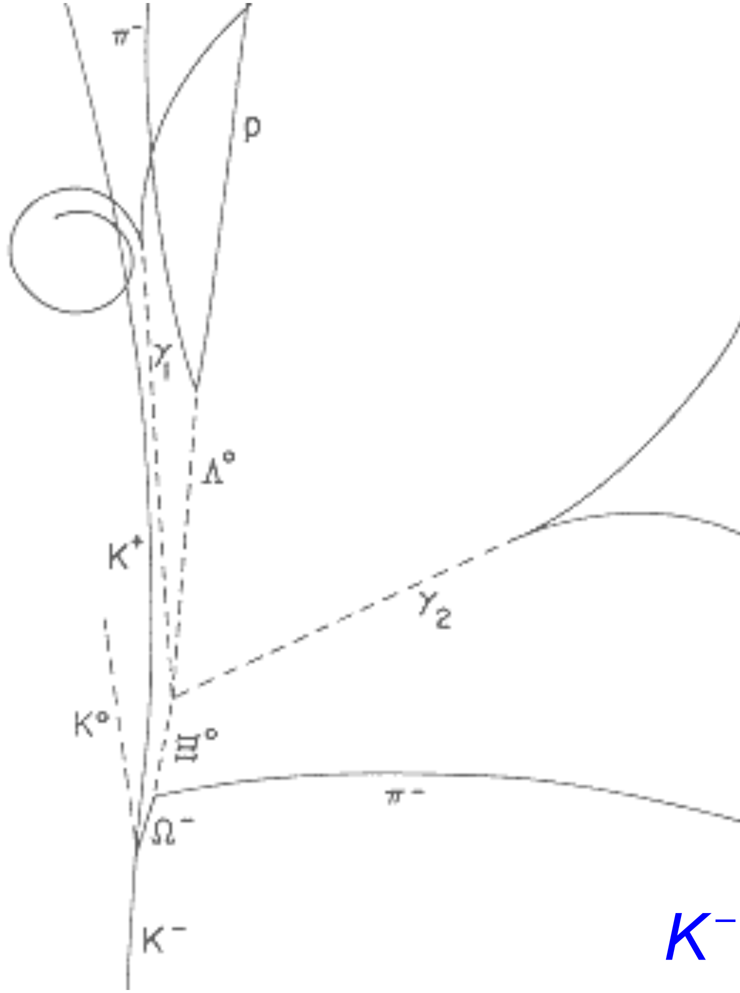
ICHEP @ CERN (1962)

Brookhaven bubble chamber, 80000 pictures !



1000 liters of liquid Hydrogen





$$K^{-}p \rightarrow \Omega^{-}K^{+}K^{0}$$

$$\Omega^{-} \rightarrow \Xi^{0}\pi^{-}$$

$$\Xi^{0} \rightarrow \Lambda\pi^{0}$$

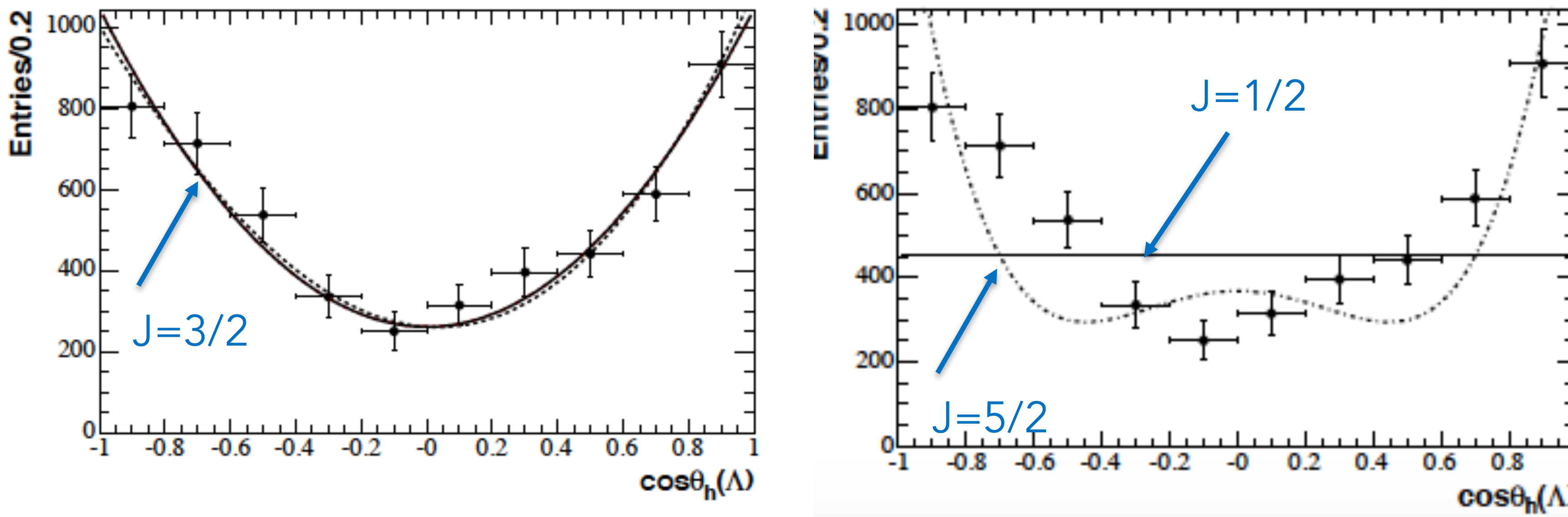
$$\Lambda \rightarrow p\pi^{-}$$

Found in 1964, mass as predicted
Proof of SU(3) classification

And in 2006 :

Measurement of the Spin of the Ω^- Hyperon at $B\mathrm{A}B\mathrm{AR}$

$\Xi_c \rightarrow \Omega$ K and $\Omega \rightarrow \Lambda$ K



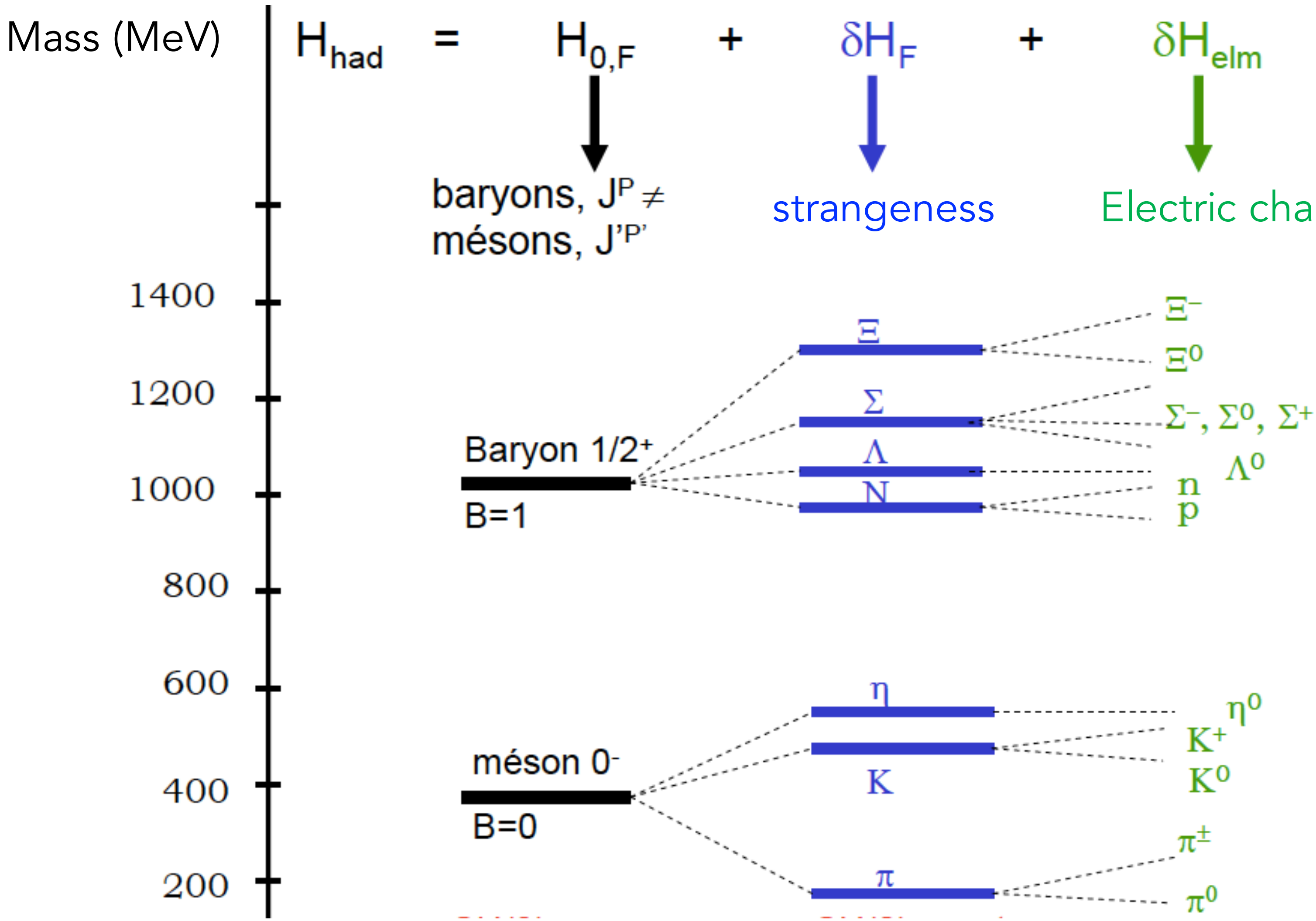
In conclusion, the angular distributions of the decay products of the Ω^- baryon resulting from Ξ_c^0 and Ω_c^0 decays are well-described by a function $\propto (1 + 3\cos^2\theta_h)$. These observations are consistent with spin assignments 1/2 for the Ξ_c^0 and the Ω_c^0, and 3/2 for the Ω^-. Values of 1/2 and greater than 3/2 for the spin of the Ω^- yield C.L. values significantly less than 1% when spin 1/2 is assumed for the parent charm baryon.

But ….

$\pi^{\pm}$	0^-	140 MeV	p	$½^+$	938 MeV
π^0	0^-	135	n	$½^+$	940
$K^{\pm}$	0^-	494	Λ	$½^+$	1160
$K^0, \overline{K}^0$	0^-	498	Σ^+	$½^+$	1189
η	0^-	549	Σ^0	$½^+$	1192
η'	0^-	958	Σ^-	$½^+$	1197
$\rho^{\pm}, \rho^0$	1^-	770	Ξ^0	$½^+$	1315
ω	1^-	783	Ξ^-	$½^+$	1321
K^*	1^-	892	Ω	$3/2^+$	1672
ϕ	1^-	1020			

The masses in a given multiplet are quite different …
➔ SU(3)-flavour is not a very good symmetry

Sketch of the symmetry :



SU(2)-isospin conserved
SU(3)-flavour broken

SU(2)-isospin broken
SU(3)-flavour broken

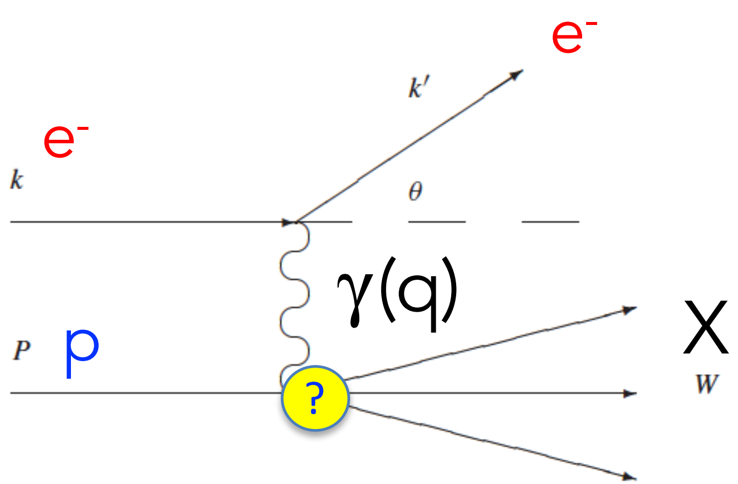
But are those quarks just artificial mathematical concepts or are they real ?

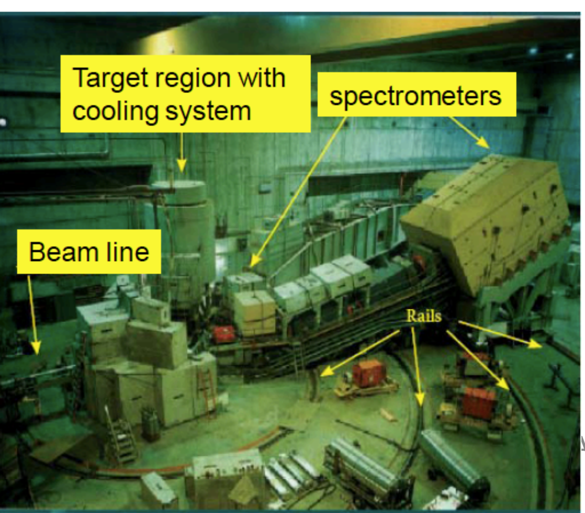
Deep Inelastic Scattering (DIS)

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

$$Q^2 = -q^2$$

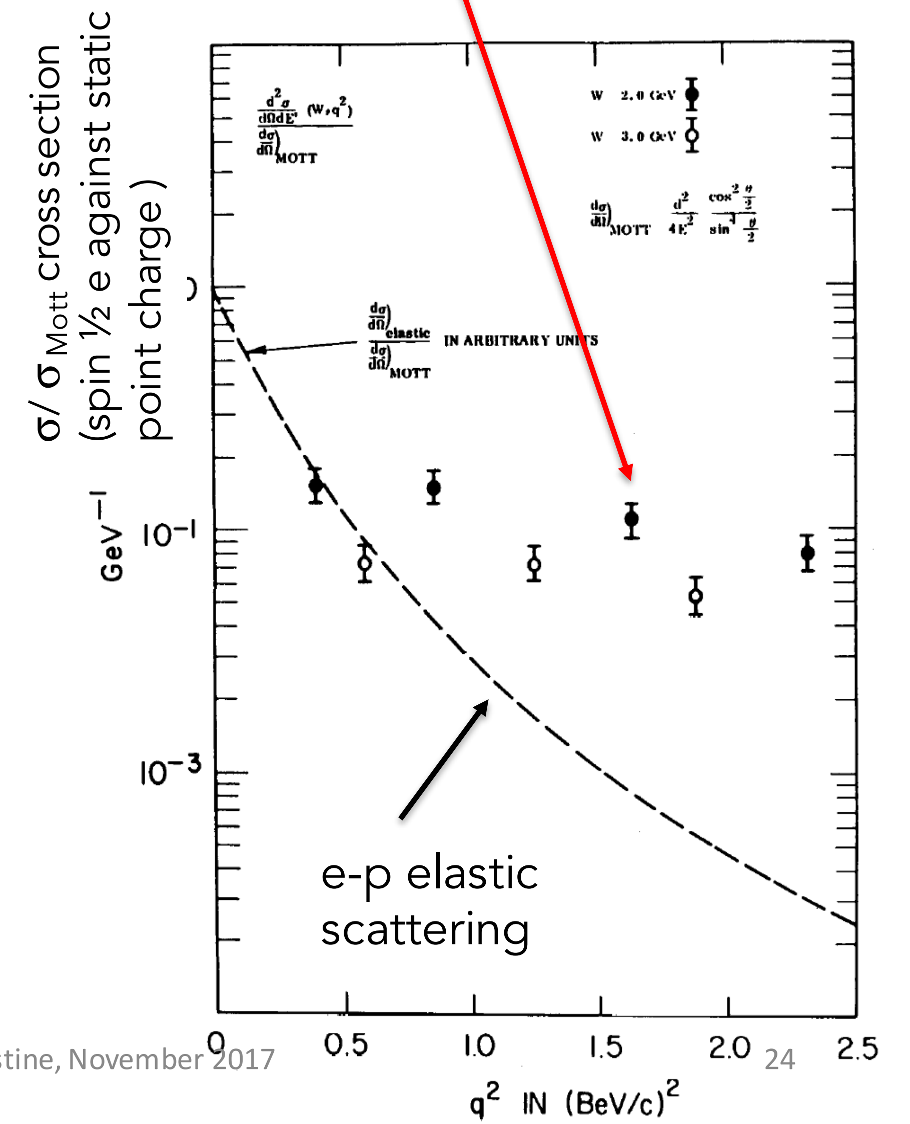
$$W^2 = M_X^2 = (p_p + q)^2$$

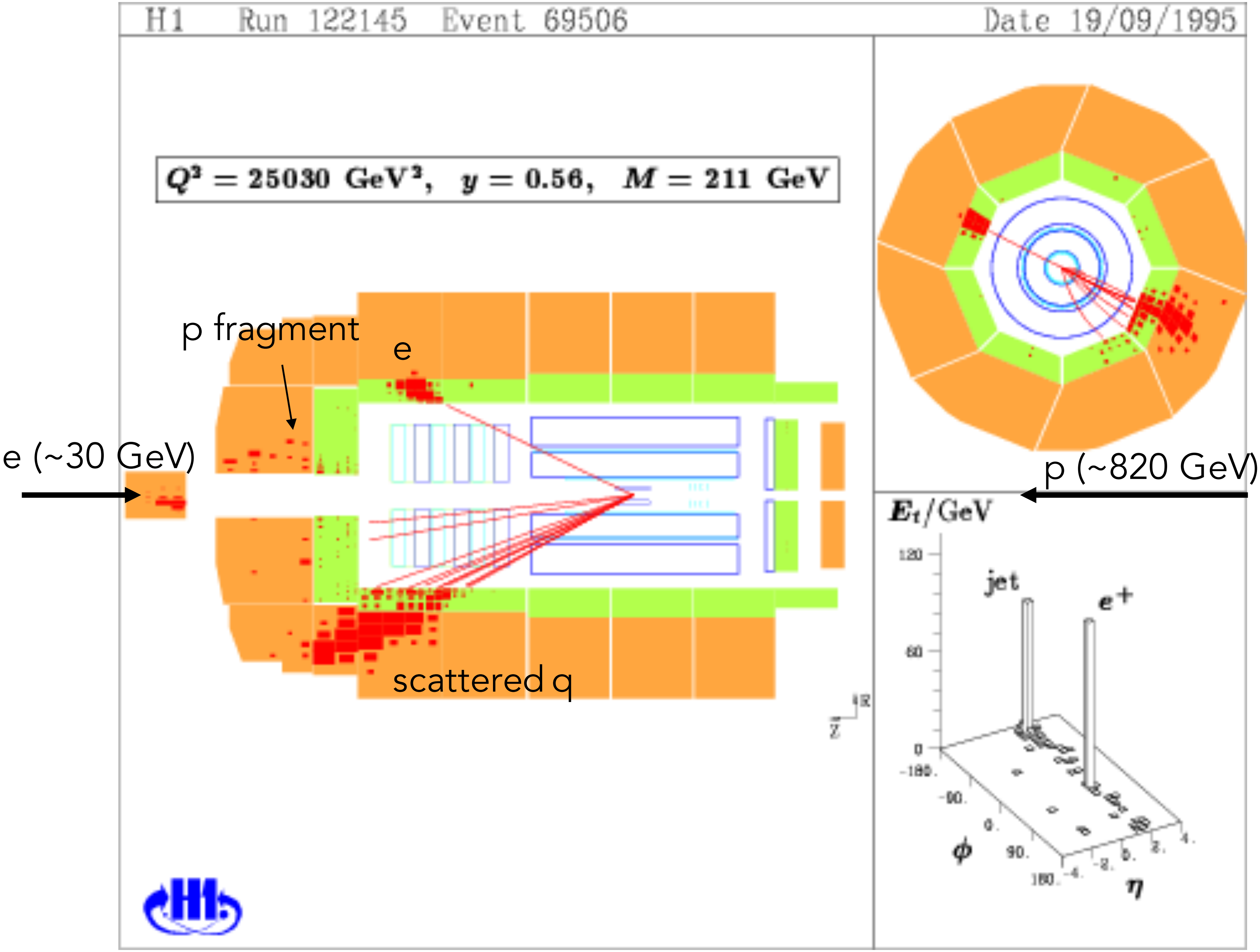




SLAC 1969

Evidence for internal substructure: weak decrease with q^2




H1 Run 122145 Event 69506 Date 19/09/1995
$Q^2 = 25030\ \mathrm{GeV}^2, \quad y = 0.56, \quad M = 211\ \mathrm{GeV}$
p fragment
e
e (~30 GeV)
scattered q
p (~820 GeV)
E_t/GeV
jet
e^+
ϕ
η

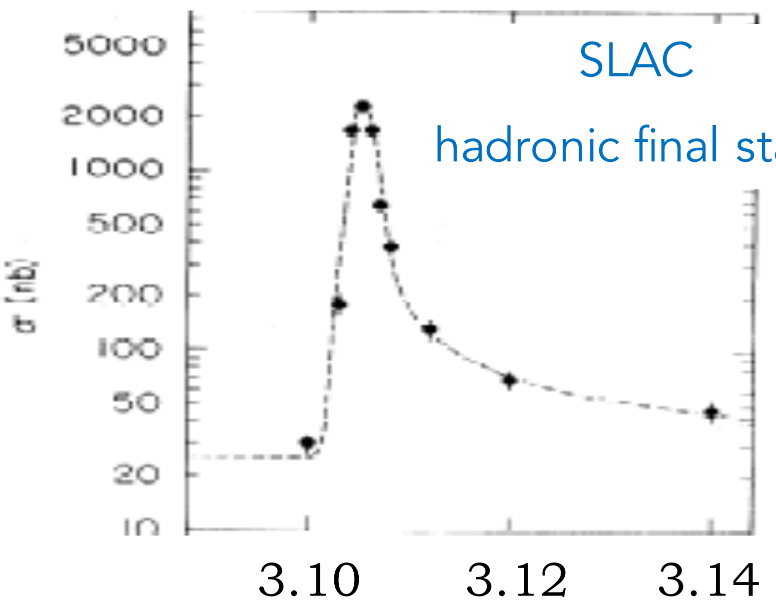
In 1969 : evidence for the existence of quarks inside the proton
… In fact more quarks were discovered soon after

1974 SLAC (e^+e^- collider) and Brookhaven (p on a Be target)

Discovery of a resonance : m ~ 3.1 GeV , τ~10^{-20} s

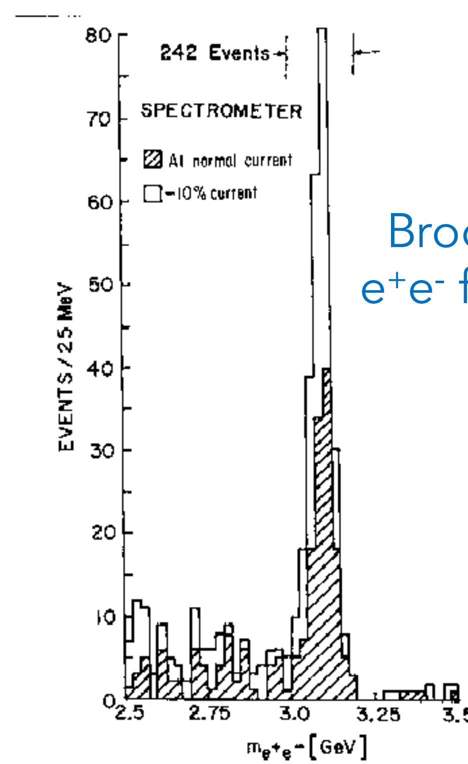
observed both in hadronic and electronic final state

J/ψ ($c\bar{c}$)



SLAC

hadronic final state



Brookhaven

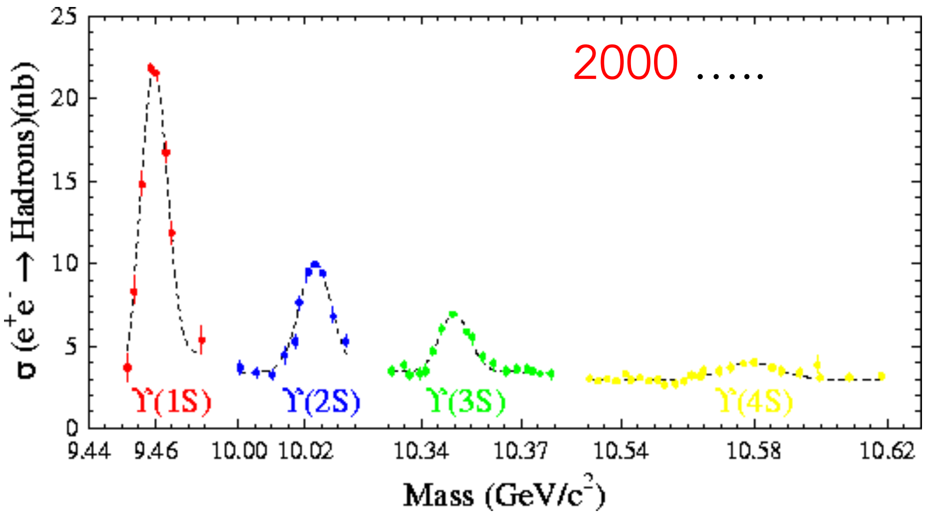
e^+e^- final state

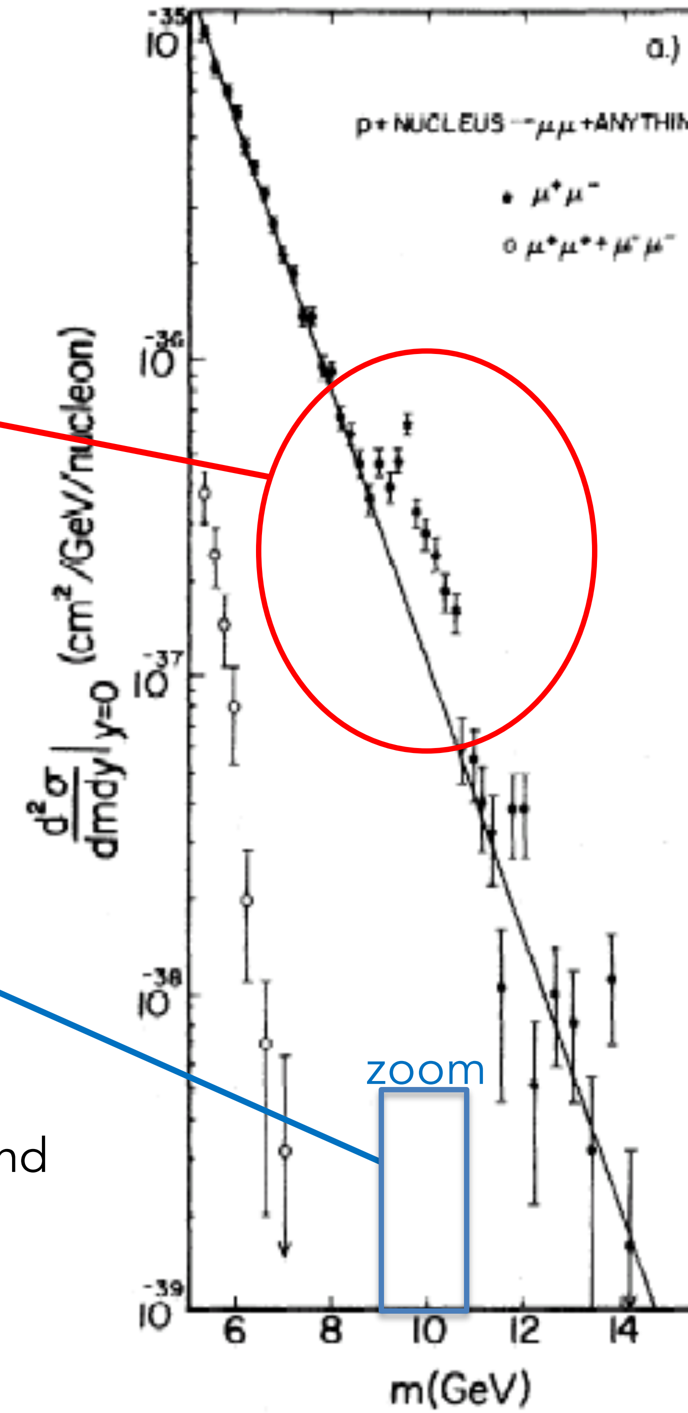
1977 Fermilab : discovery of the Υ serie

m ~ 9.5-10.5 GeV, $b\bar{b}$ resonances

Excess wider than the experimental resolution $\Rightarrow$ several resonances

B factories : $\Upsilon(4S)$ decays into a $B^0\bar{B}^0$ ou B^+B^- pair (CLEO, BaBar, BELLE)





At LEP (1990) , experimental evidence for B-mesons and B-baryons and first studies of their properties

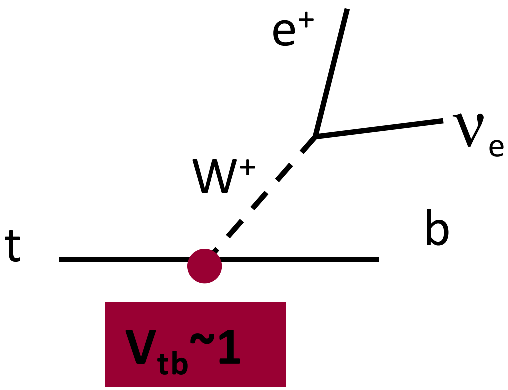
2000 : Tevatron Fermilab

2010 : LHCb

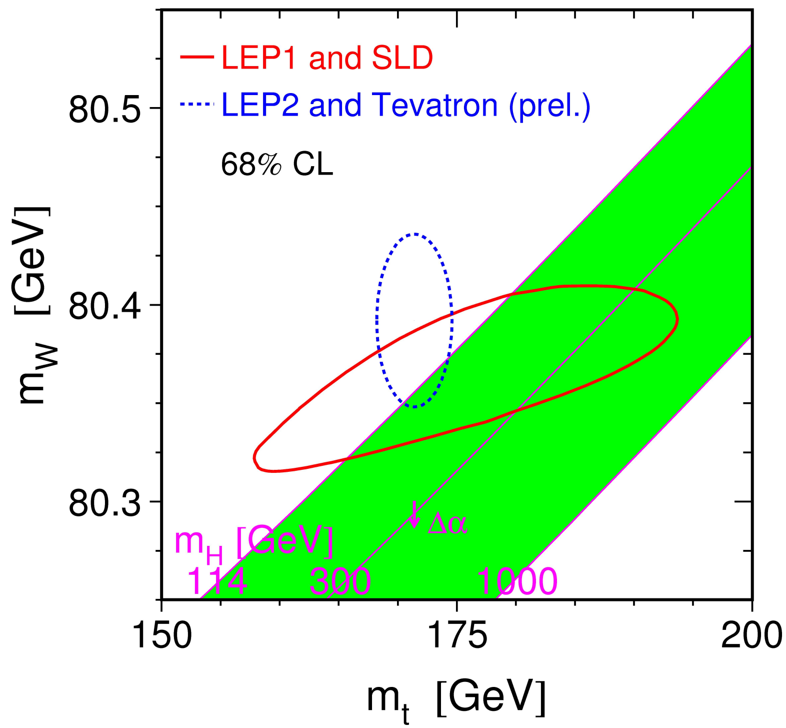
and … the 6th quark !

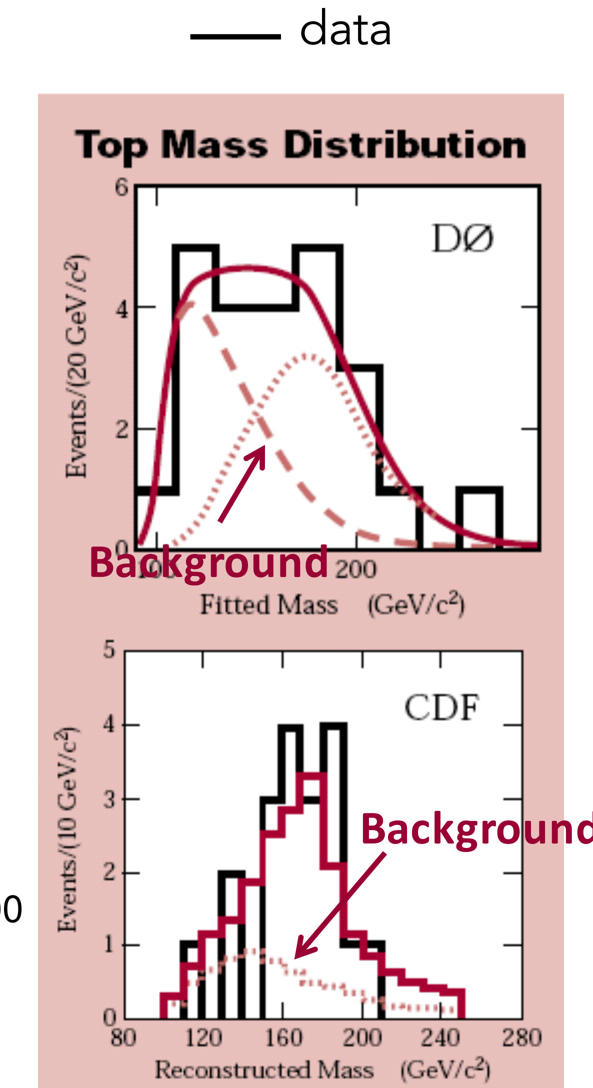
1995 Fermilab (USA) CDF et D0 experiments

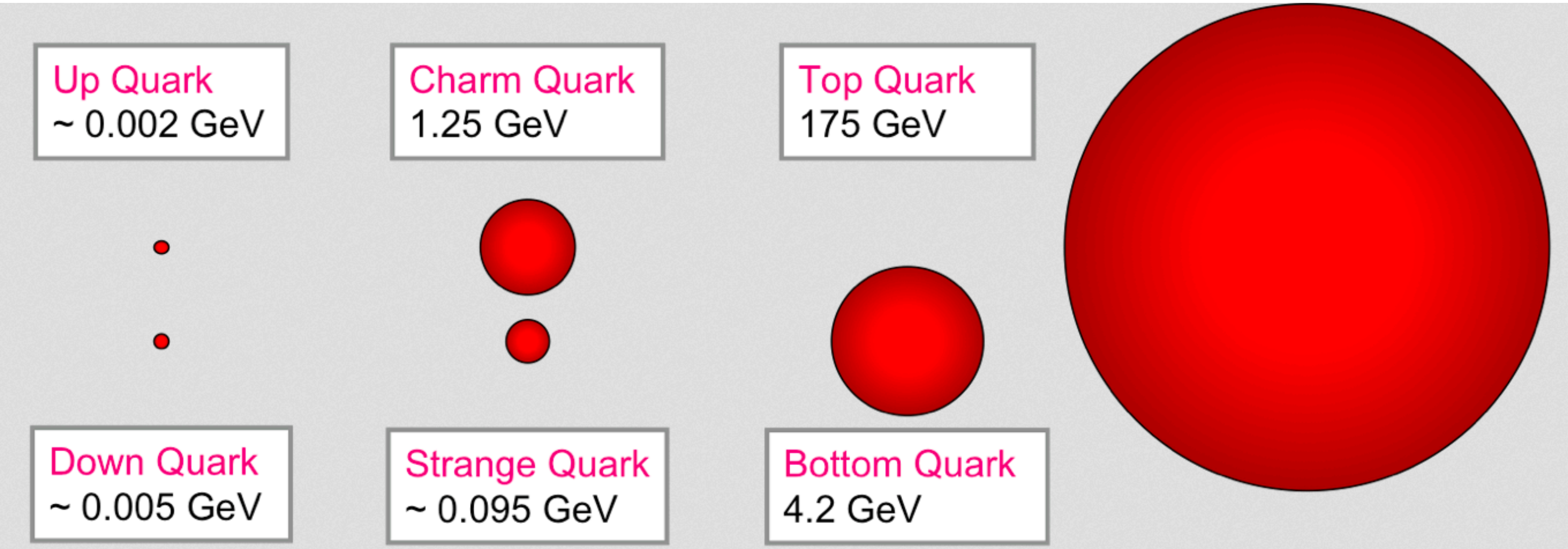
Top is very heavy (40x b) ⇒ it decays before it hadronizes



ICHEP Conf July 2006







quarks

1st family 2nd family 3rd family

Very different masses … no explanation why !

5 quarks can hadronize

Why not the top quark ?

The decay $\propto m^5 \Rightarrow$ extremely short lifetime

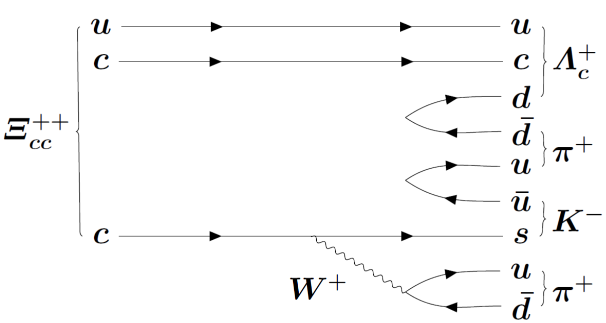
Hadronization time $\sim 10^{-23}$ s

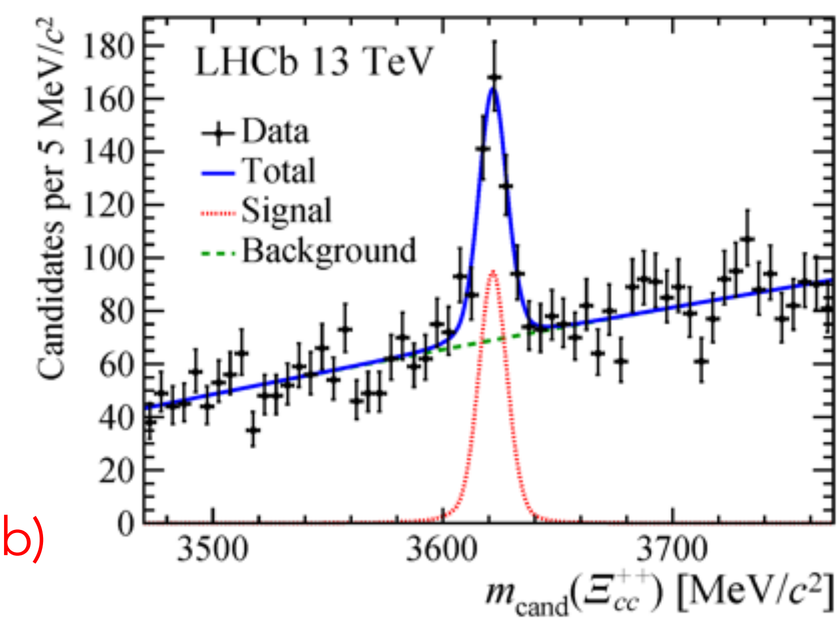
$\Rightarrow$ no top hadrons

A lot of possible hadrons, most of them have been discovered but not all of them !

A baryon made of (ccu) : Ξ_{cc}^{++}

Summer 2017

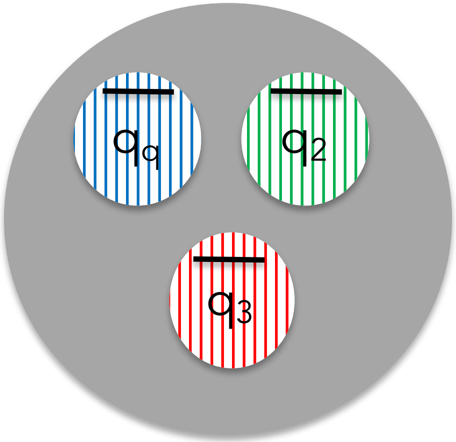


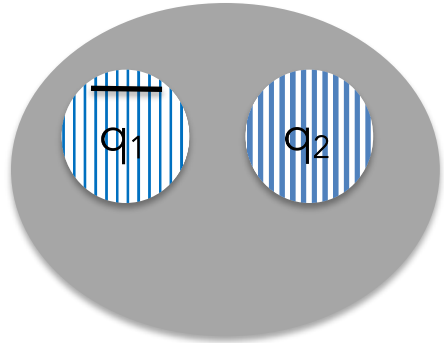


First baryon containing two heavy (c or b) quarks

$\Rightarrow$ very interesting tool for testing QCD

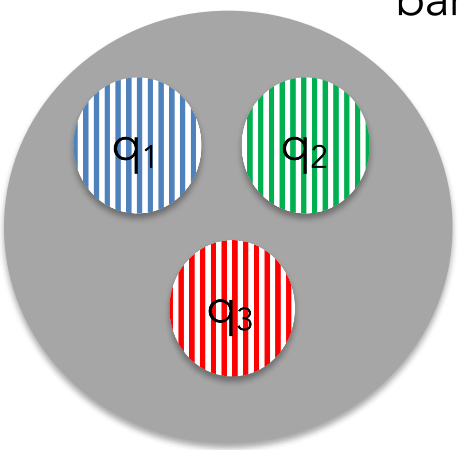
Mesons, baryons … and more ?





mesons

baryons



Gell-Man & Zweig : multiquarks objects are possible

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A SCHEMATIC MODEL OF BARYONS AND MESONS *

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Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G. Zweig *)
CERN - Geneva

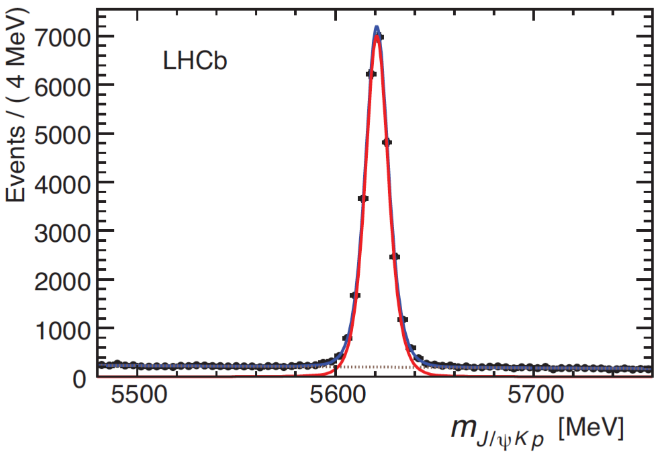
ABSTRACT

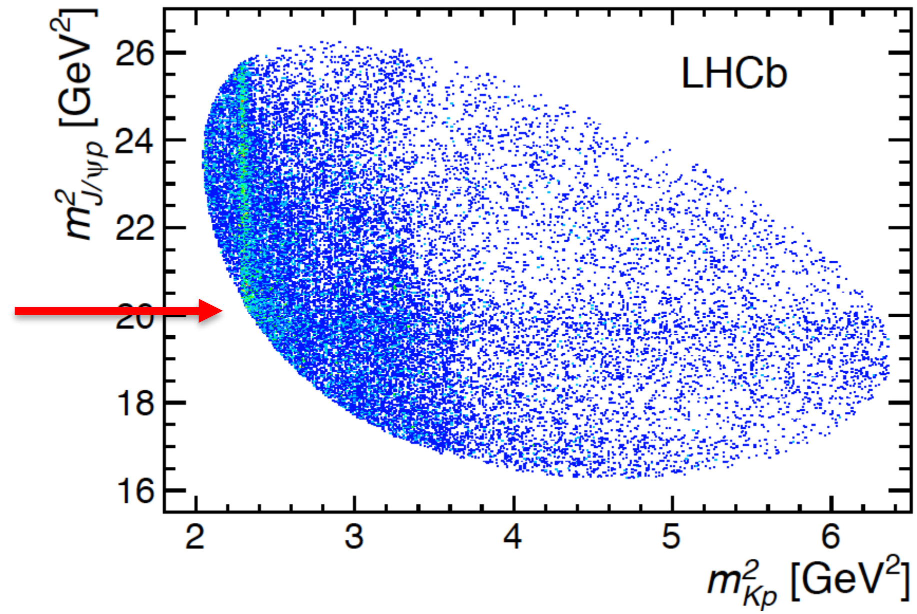
Both mesons and baryons are constructed from a set of three fundamental particles called aces. The aces break up into an isospin doublet and singlet. Each ace carries baryon number $\frac{1}{3}$ and is consequently fractionally charged. SU_3 (but not the Eightfold Way) is adopted as a higher symmetry for the strong interactions. The break-

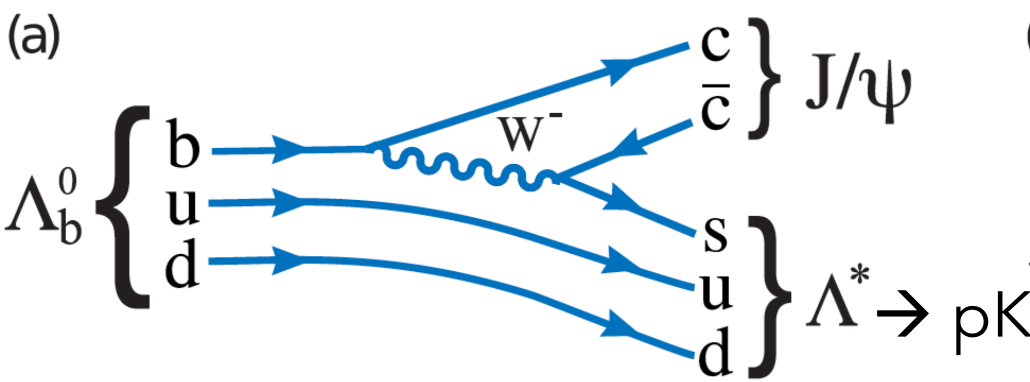
baryons : $qqqq\bar{q}$

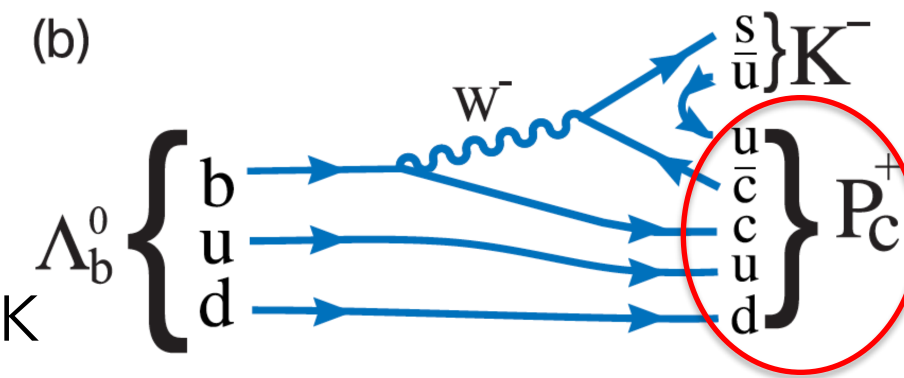
mesons : $q\bar{q}\;q\bar{q}$

$\Lambda_b \rightarrow J/\psi pK$ decays (2015)





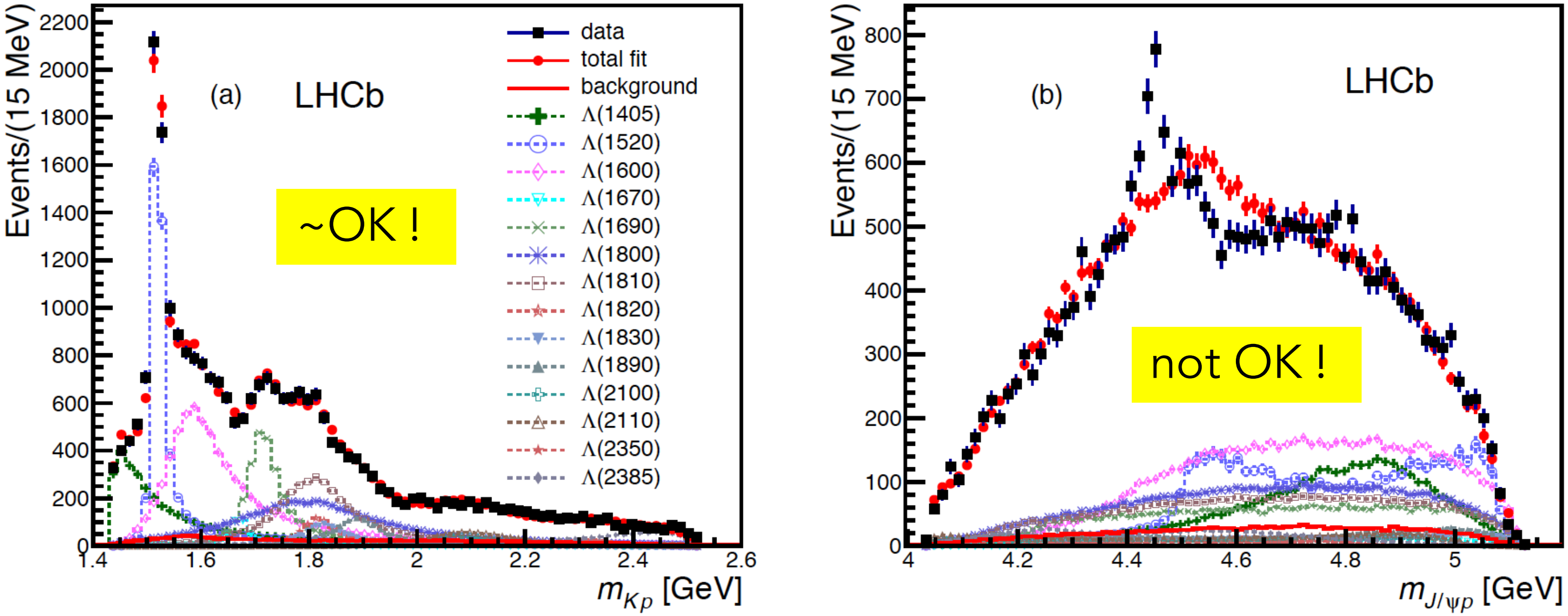




A pentaquark ?

short-lived ~10^{-23} s resonances :
mass peaks
angular distributions (unique J^P quantum numbers)

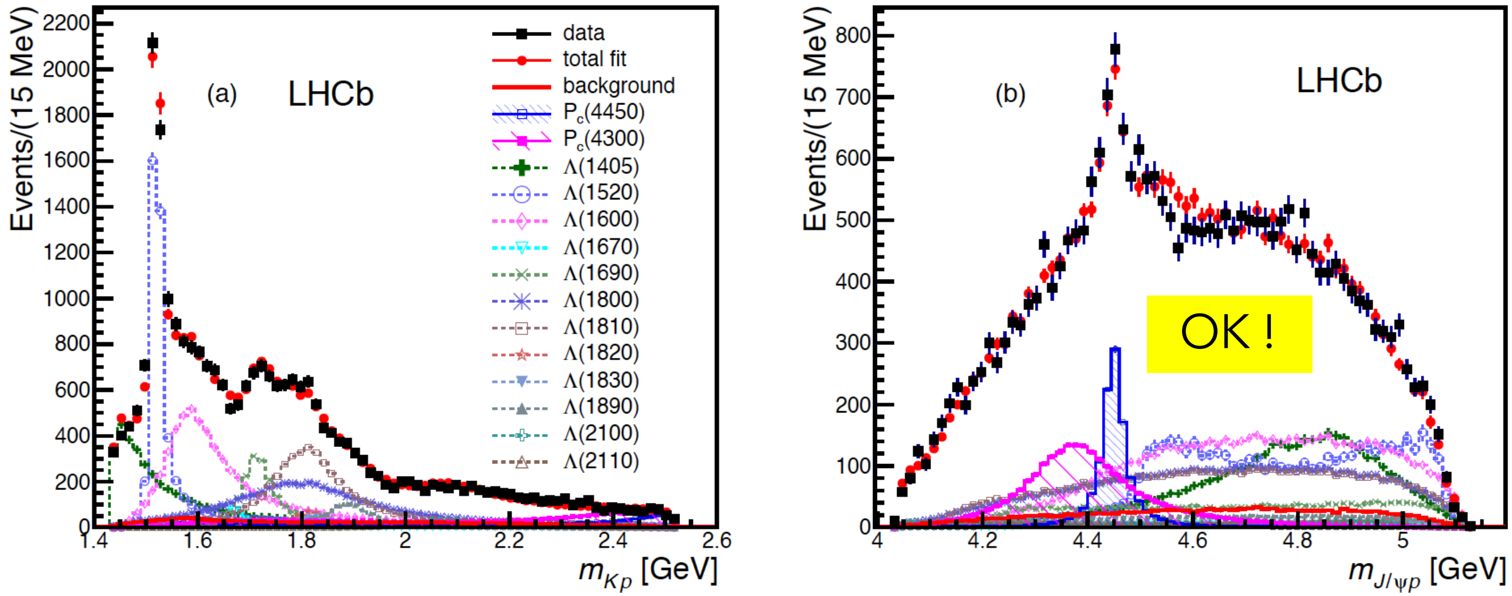
Analysis with all what is known :



Data

Fit

Adding 2 P_c states:



Data

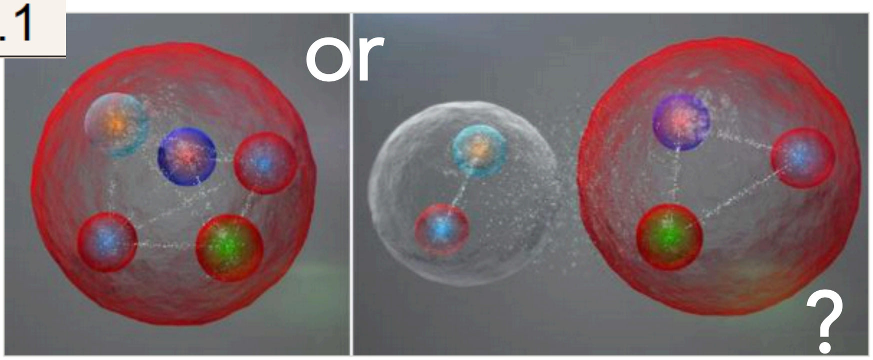
Fit

Mass (MeV)	Width (MeV)	Fit fraction (%)
4380±8±29	205±18±86	8.4±0.7±4.2
4449.8±1.7±2.5	39±5±19	4.1±0.5±1.1

PRL 115 (2015) 072001

$J^P=(3/2^-, 5/2^+)$

2015 result

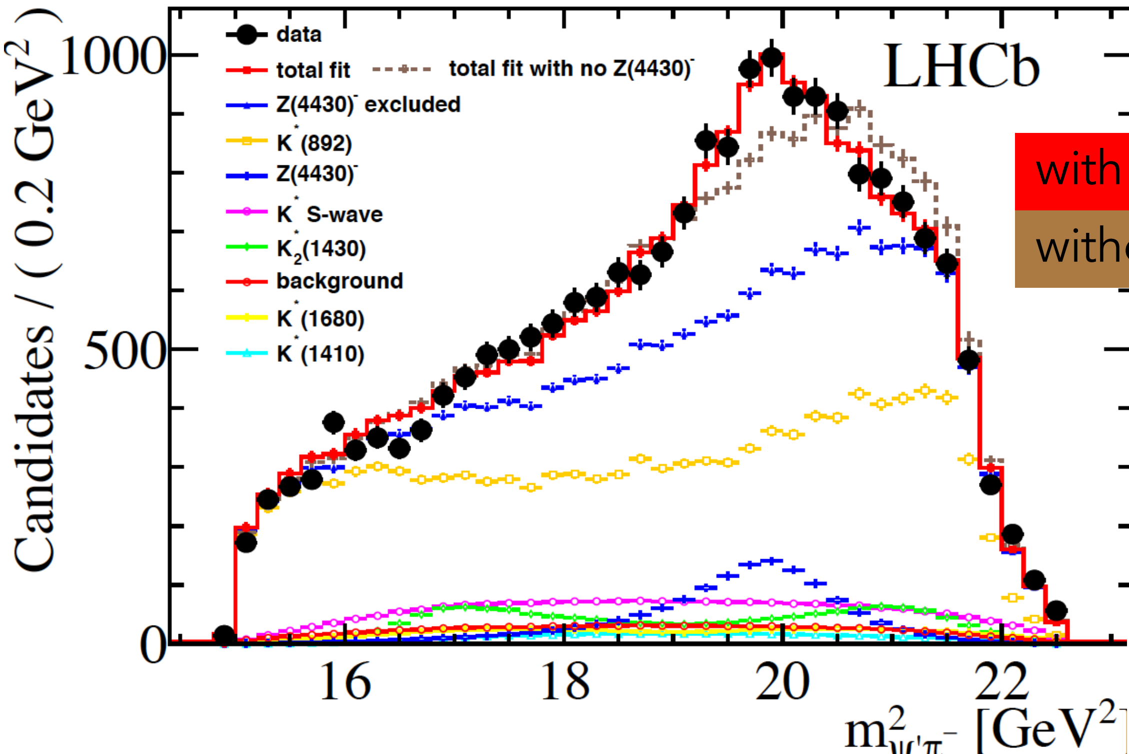


Possible layout of the quarks in a pentaquark particle. The five quarks might be tightly bound (left). They might also be assembled into a meson (one quark and one antiquark) and a baryon (three quarks), weakly bound together (Image: Daniel Dominguez)

But also a tetraquark !

Belle, BaBar, LHCb

$B^0 \rightarrow \psi'\pi^- K^+$, peak in $m(\psi'\pi^-)$, charged charmonium state must be exotic, not $q\bar{q}$

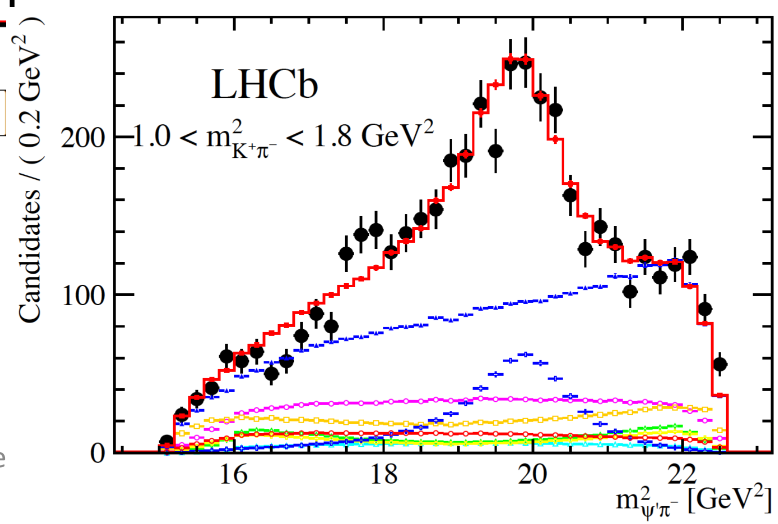


with Z(4430)

without Z(4430)

$J^P=1^+$

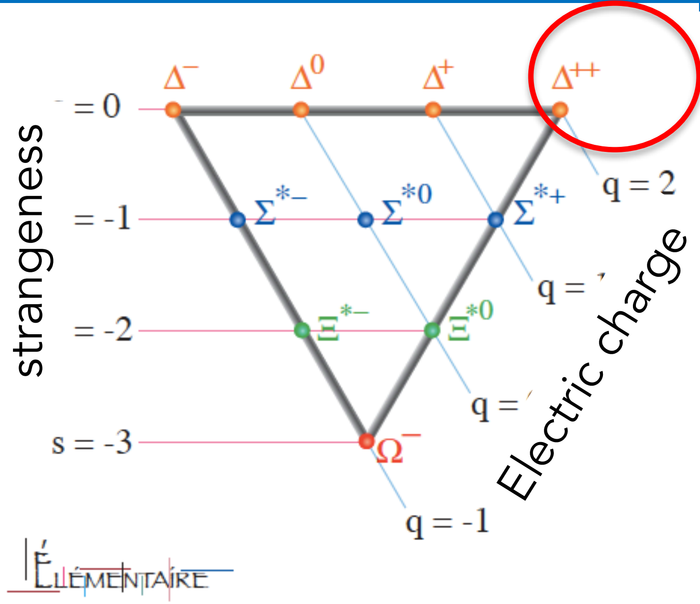
PRL 112 (2014) 222002



First observed by Belle in 2008
LHCb ruled out other possibilities in 2014

Color and QCD

QCD : the color



3 identical quarks all spin up

Pauli exclusion principle

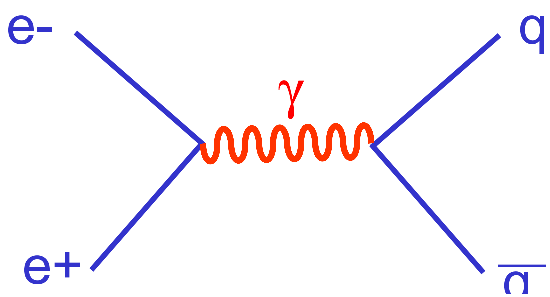
→ color

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

→ 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



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

$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_C \sum_i q_i^2 = N_C\left[\left(\frac{1}{3}\right)^2 + \left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2\right] = N_C \frac{11}{9}$$

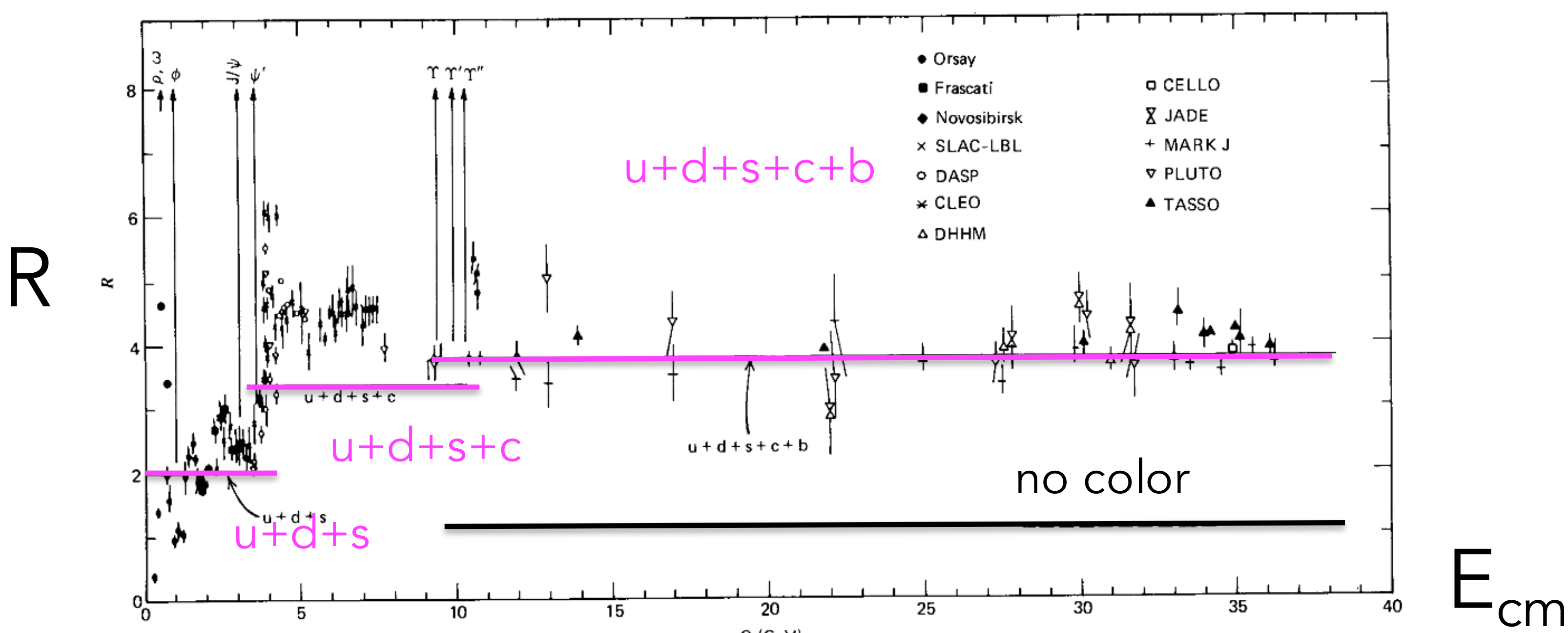
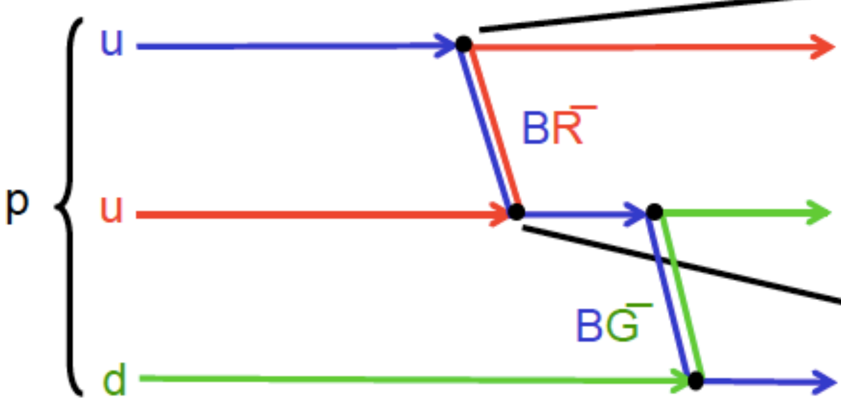


Fig. 11.3 Ratio R of (11.6) as a function of the total e^-e^+ center-of-mass energy. (The sharp peaks correspond to the production of narrow 1^- resonances just below or near the flavor thresholds.)

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

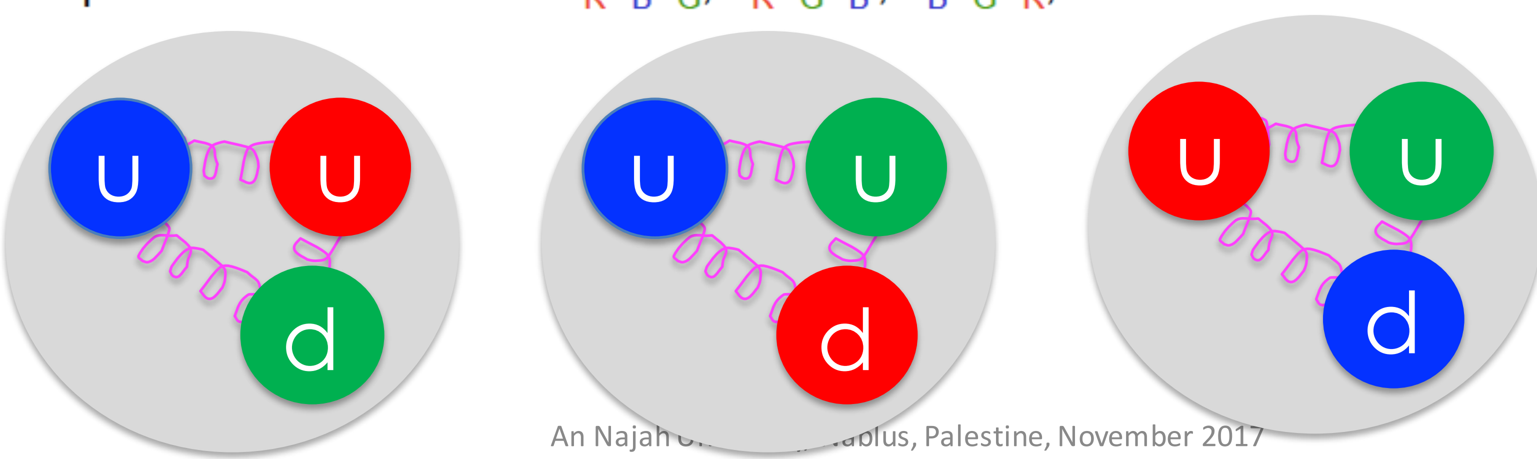
Proton description :



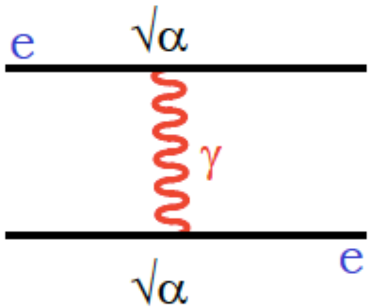
At this vertex the $B\bar{R}$ gluon transforms the $B \rightarrow R$ (removing the B, leaving the $\bar{R}$ which is equilibrated by the R)

$R\,\bar{R}$ annihilate, the B remains. $R \rightarrow B$

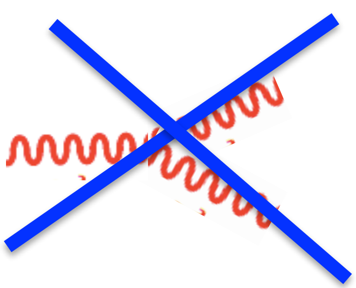
The proton is a mixture of : $u_R u_B d_G$, $u_R u_G d_B$, $u_B u_G d_R$, ….



QED :

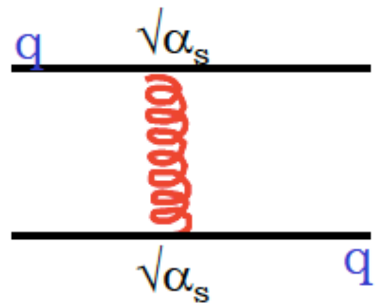


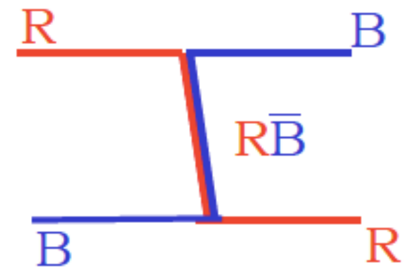
1 photon :
- massless
- electrically neutral



Does not exist

QCD :





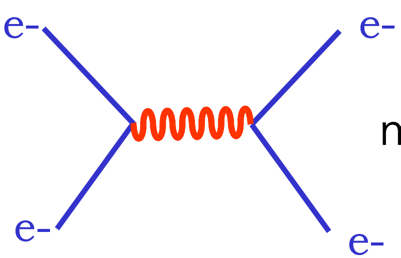
8 gluons :
- massless
- colored

gluon self-interaction

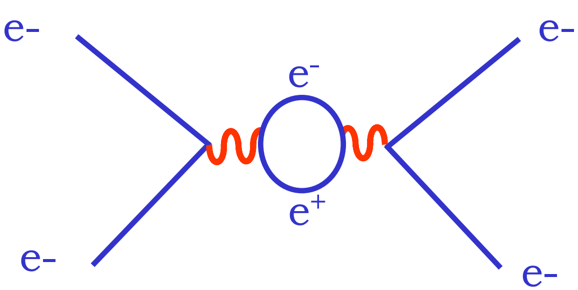
!

QED :

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

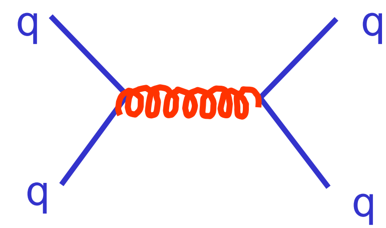


modified by

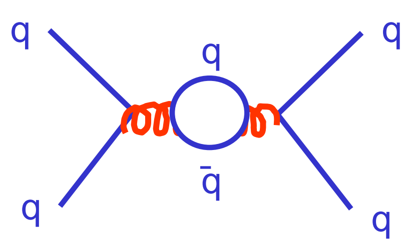


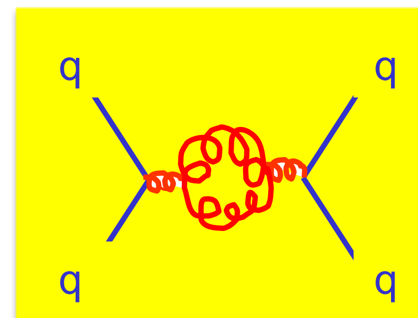
QCD :

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



modified by



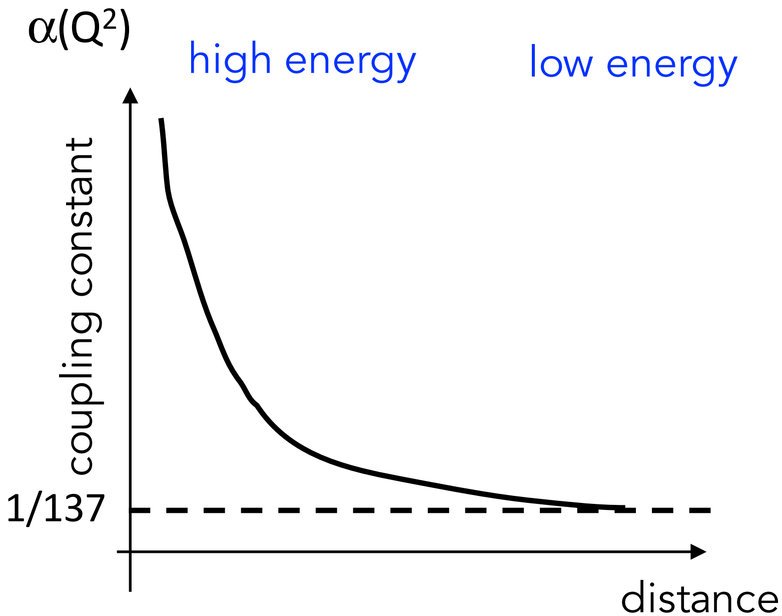


n_f : number of flavours

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

QED :

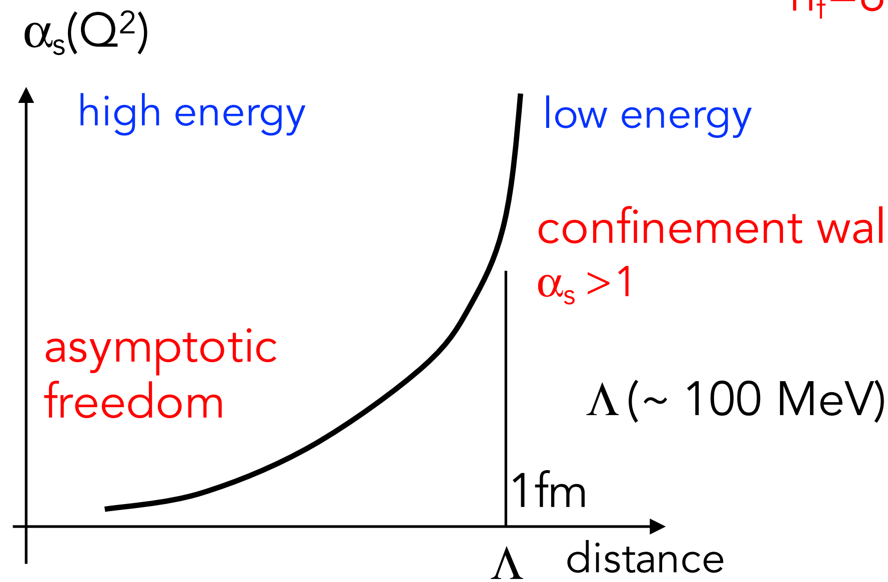
$$\alpha(Q^2) = \frac{\alpha(\mu^2)}{1 + \frac{\alpha(\mu^2)}{4\pi}\left(-\frac{4}{3}\right) log\left(\frac{Q^2}{\mu^2}\right)}$$



QCD :

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

$n_f=6$



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

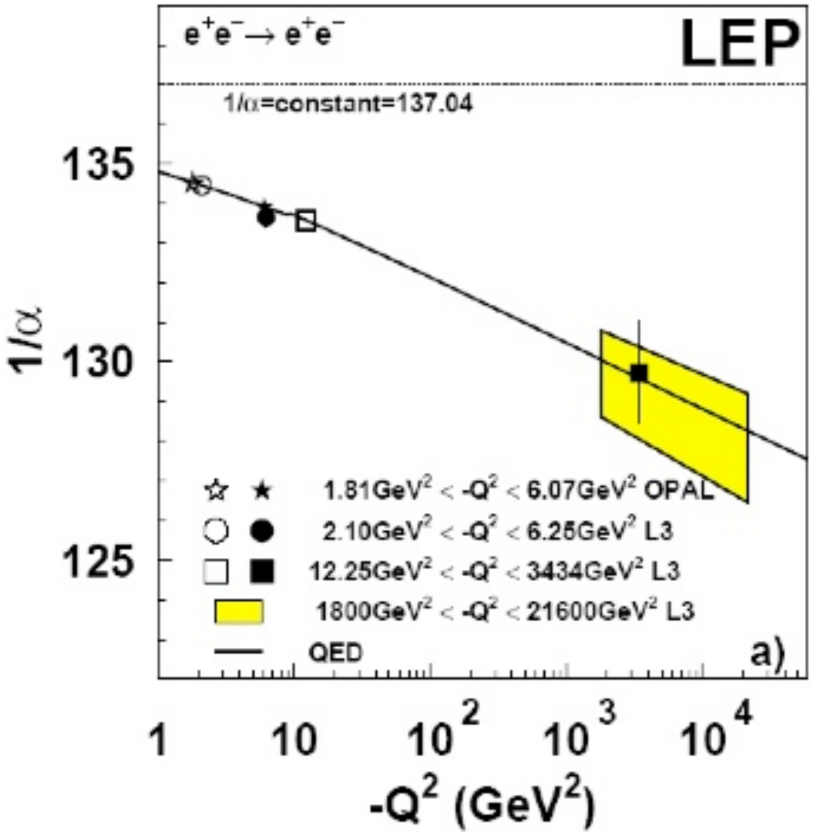
$Q^2 >> \Lambda^2$ weak coupling perturbations

non intuitive!

Colour confinement

QED :

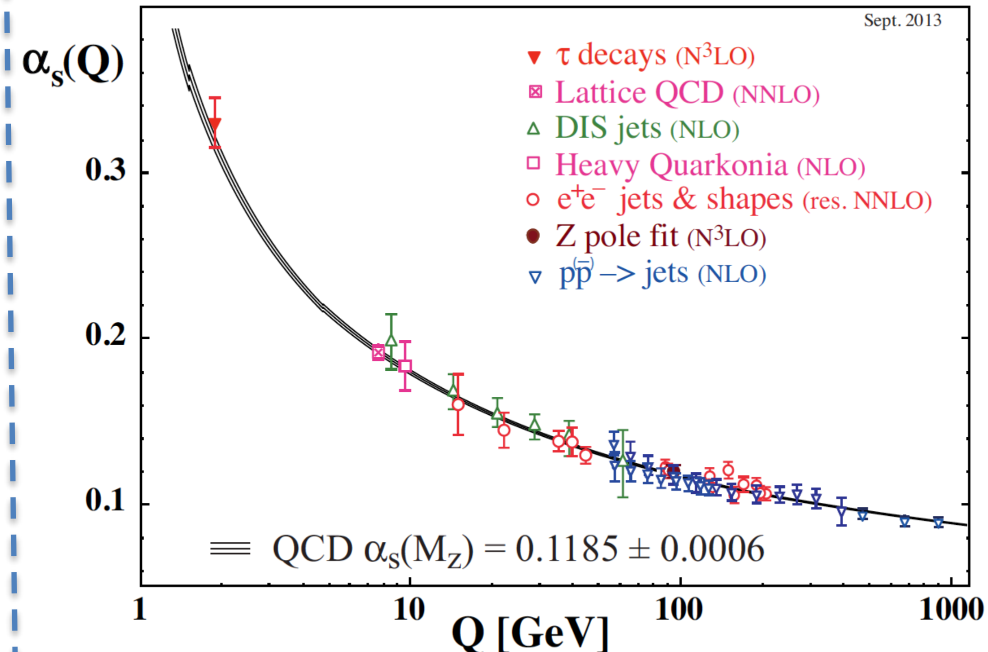
Evolution of $1/\alpha$ as a function of E



When the energy increases (the distance decreases) α increases

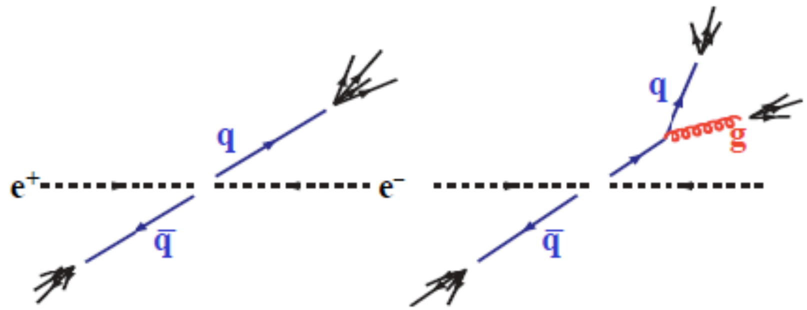
QCD :

Evolution of α_s as a function of E

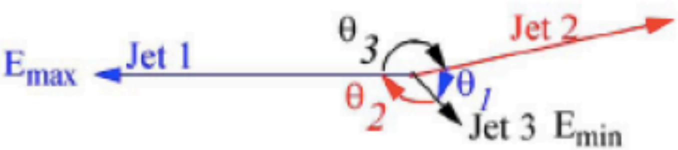


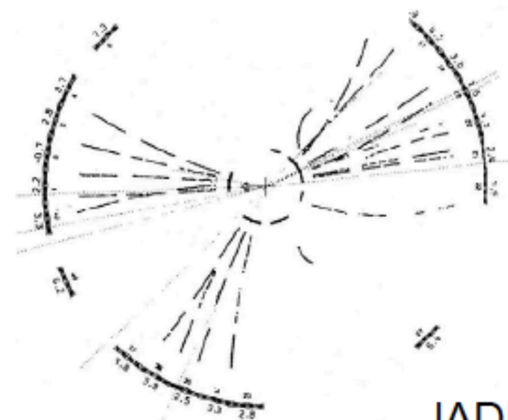
When the energy increases (the distance decreases) α_s decreases

First experimental evidence of 3 jets events : 1979 at PETRA e+e– collider ($\sqrt{s}$= 31 GeV) at DESY



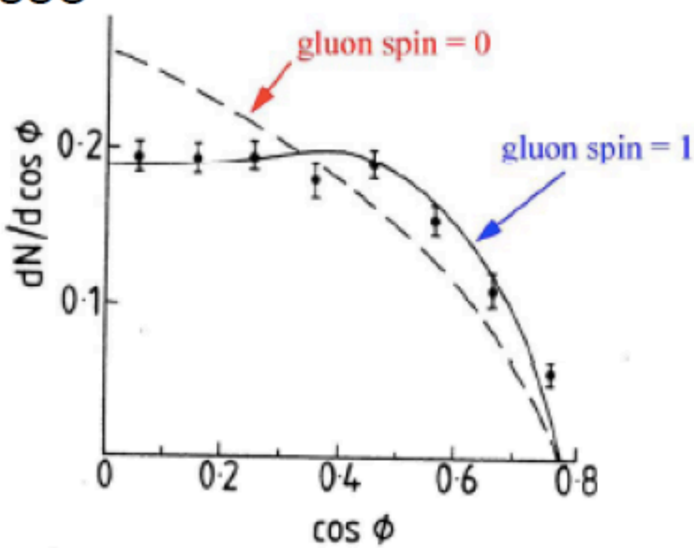
Gluon radiation probability $\propto \alpha_s$
$\Rightarrow \propto \alpha_s$ measurement





JADE

TASSO

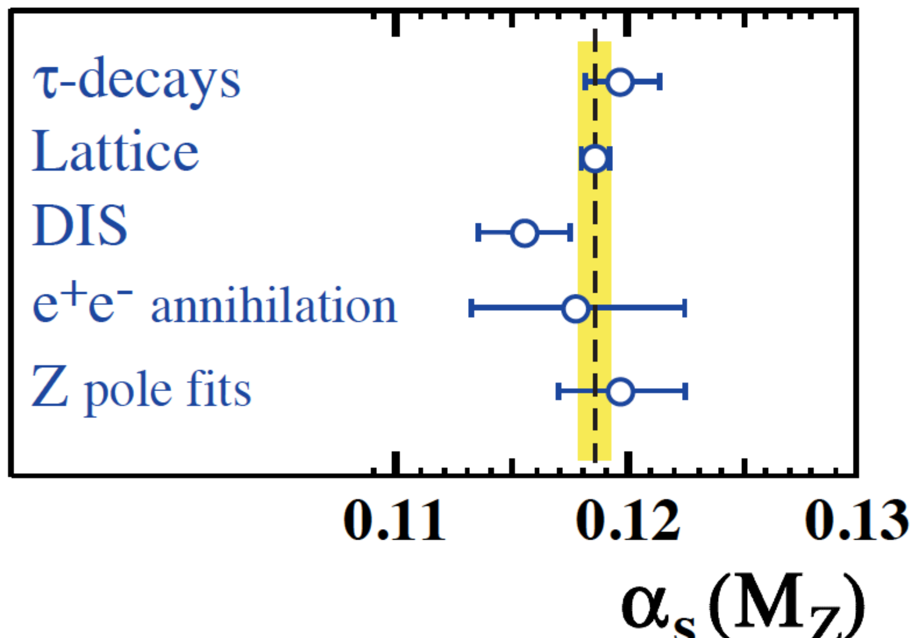


$$\sin\phi = \frac{\sin\theta_2 - \sin\theta_3}{\sin\theta_1}$$

Gluon spin measurement

α_S measurements

evolved from the energy where they are performed to the Z mass



$$\boxed{\alpha_s(M_Z^2) = 0.1185 \pm 0.0006}$$

0.5 % precision !

The measurement of α_s is very important : LHC phenomenology

Example : the Higgs is produced by gluon-gluon fusion

$\sigma_H \sim \alpha_s^2 \Longrightarrow \frac{\Delta\sigma_H}{\sigma_H} = 2\,\frac{\Delta\alpha_s}{\alpha_s}$ (in fact it is even worse due to higher order corrections)

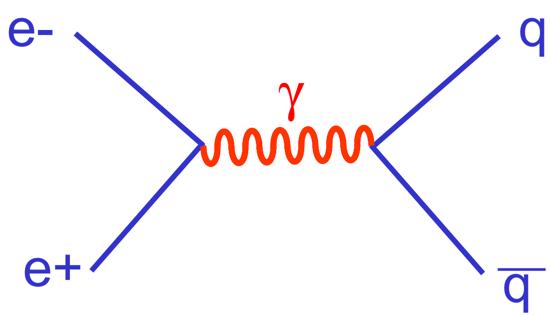
E_{CM}	σ	δ(theory)	δ(PDF)	$\delta(\alpha_s)$
2 TeV	1.10 pb	$^{+0.04\text{pb}}_{-0.09\text{pb}}\left(^{+4.06\%}_{-7.88\%}\right)$	$\pm$ 0.03 pb ($\pm$ 3.17%)	$^{+0.04\text{pb}}_{-0.04\text{pb}}\left(^{+3.36\%}_{-3.69\%}\right)$
7 TeV	16.85 pb	$^{+0.74\text{pb}}_{-1.17\text{pb}}\left(^{+4.41\%}_{-6.96\%}\right)$	$\pm$ 0.32 pb ($\pm$ 1.89%)	$^{+0.45\text{pb}}_{-0.45\text{pb}}\left(^{+2.67\%}_{-2.66\%}\right)$
8 TeV	21.42 pb	$^{+0.95\text{pb}}_{-1.48\text{pb}}\left(^{+4.43\%}_{-6.90\%}\right)$	$\pm$ 0.40 pb ($\pm$ 1.87%)	$^{+0.57\text{pb}}_{-0.56\text{pb}}\left(^{+2.65\%}_{-2.62\%}\right)$
13 TeV	48.58 pb	$^{+2.22\text{pb}}_{-3.27\text{pb}}\left(^{+4.56\%}_{-6.72\%}\right)$	$\pm$ 0.90 pb ($\pm$ 1.86%)	$^{+1.27\text{pb}}_{-1.25\text{pb}}\left(^{+2.61\%}_{-2.58\%}\right)$
14 TeV	54.67 pb	$^{+2.51\text{ pb}}_{-3.67\text{ pb}}\left(^{+4.58\%}_{-6.71\%}\right)$	$\pm$1.02 pb ($\pm$ 1.86%)	$^{+1.43\text{pb}}_{-1.41\text{pb}}\left(^{+2.61\%}_{-2.59\%}\right)$

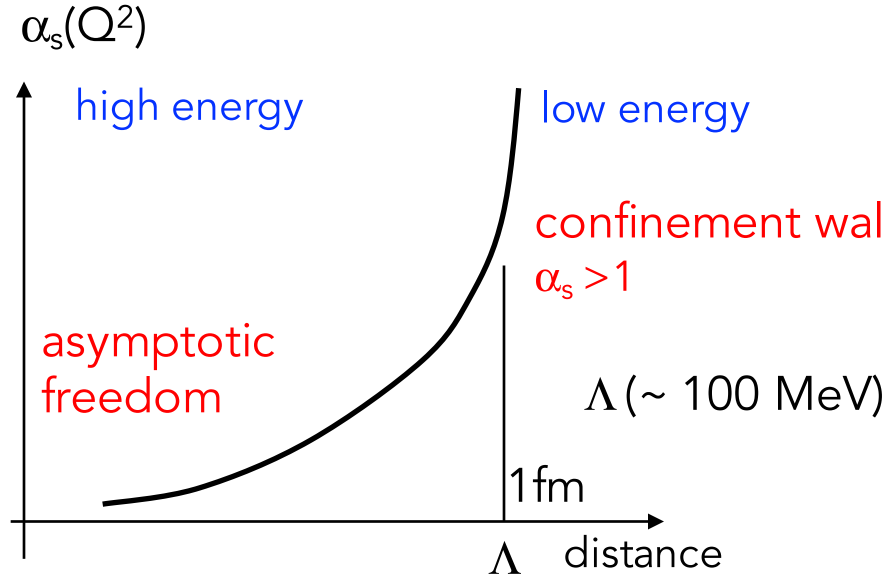
Table 10: Gluon-fusion Higgs cross-section at a proton-proton collider for various values of the collision energy.

From arXiv:1602.00695v1

Hadronization

$e^+e^- \rightarrow q\bar{q}$





but quarks are colored

→ not observed directly

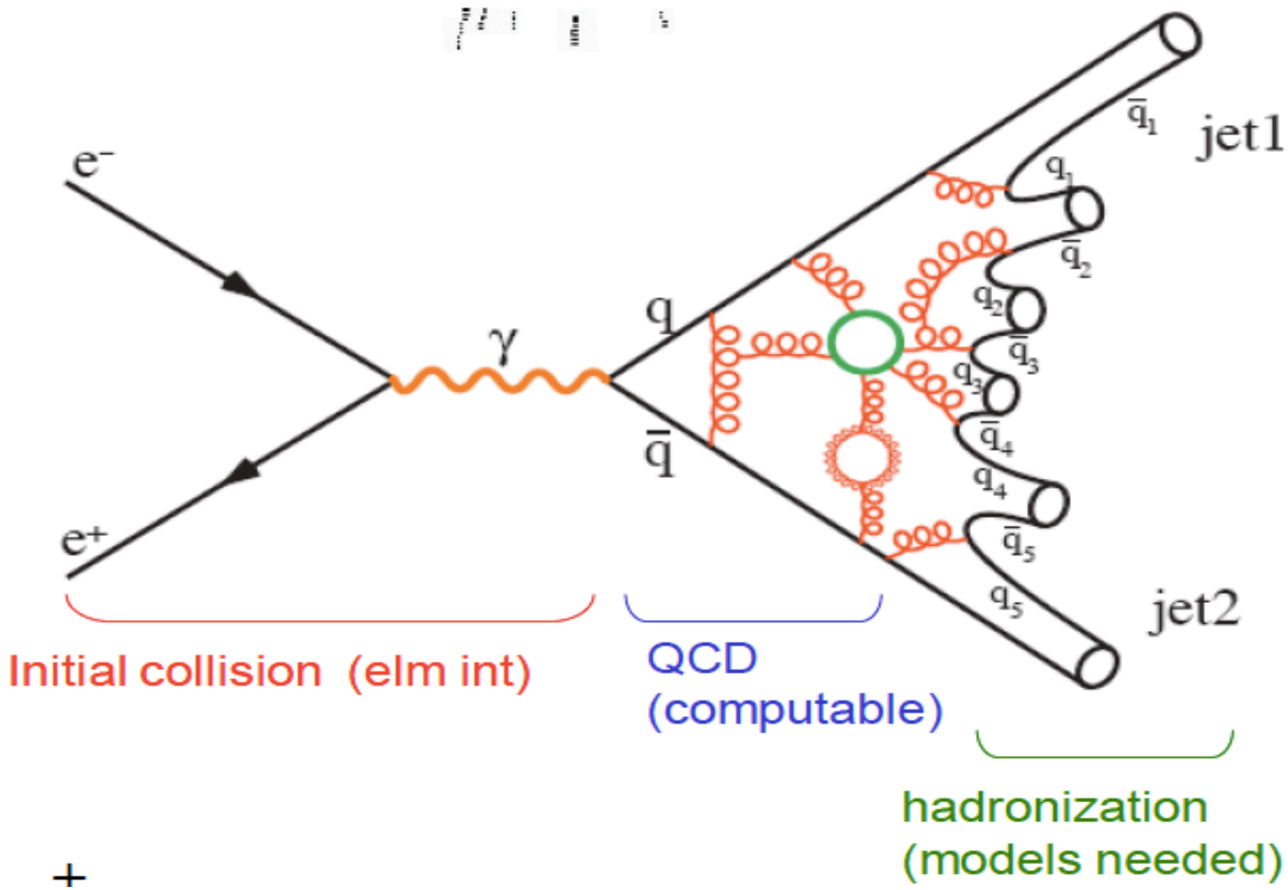
$Q^2 \sim \Lambda^2$ strong coupling ~~perturbations~~

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

- The strong interaction coupling constant is too large beyond 1 fm (pertubative theory breaks down)
- Models needed for quarks → hadrons

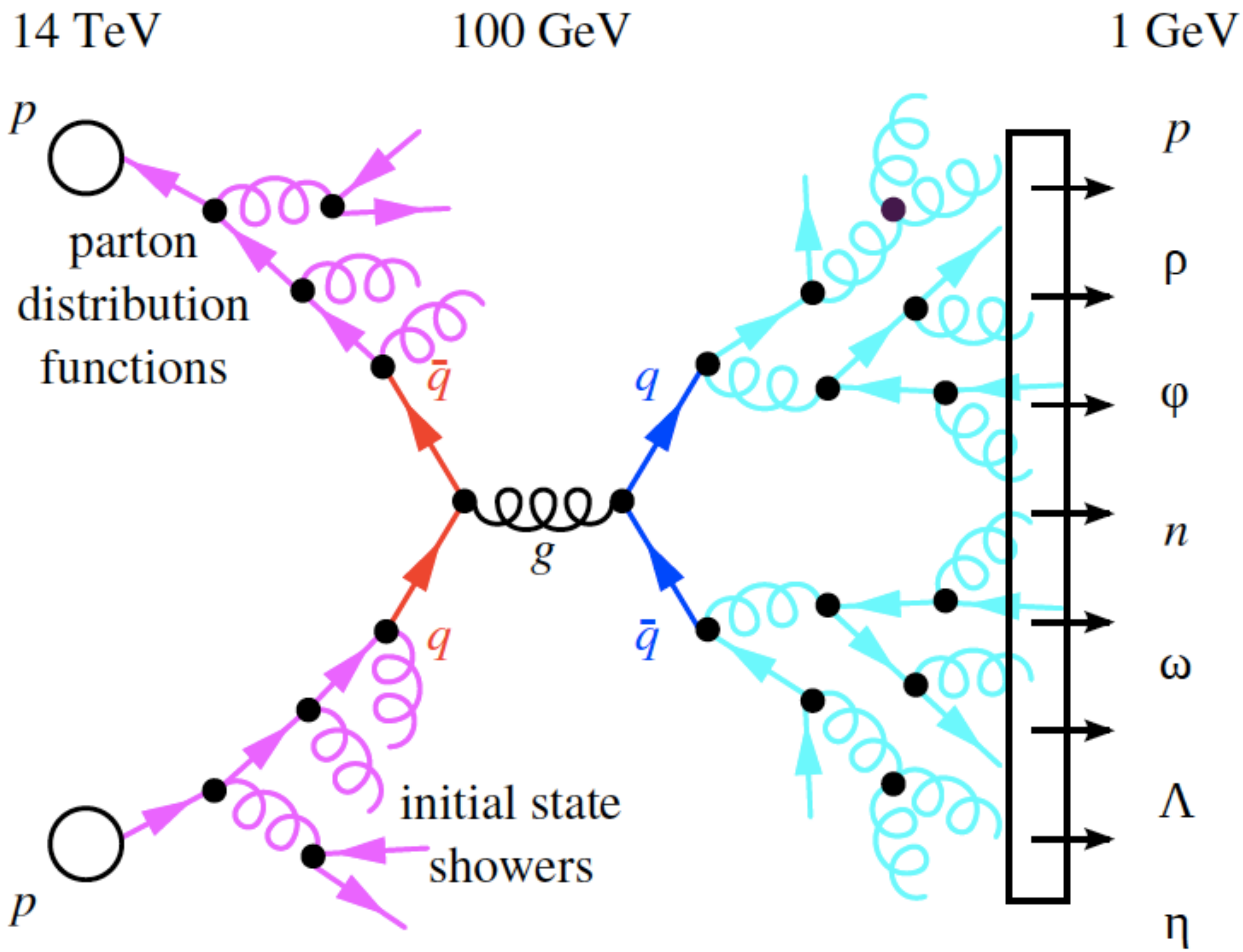
Hadronization model

$q\bar{q}$ production at e+ e- colliders



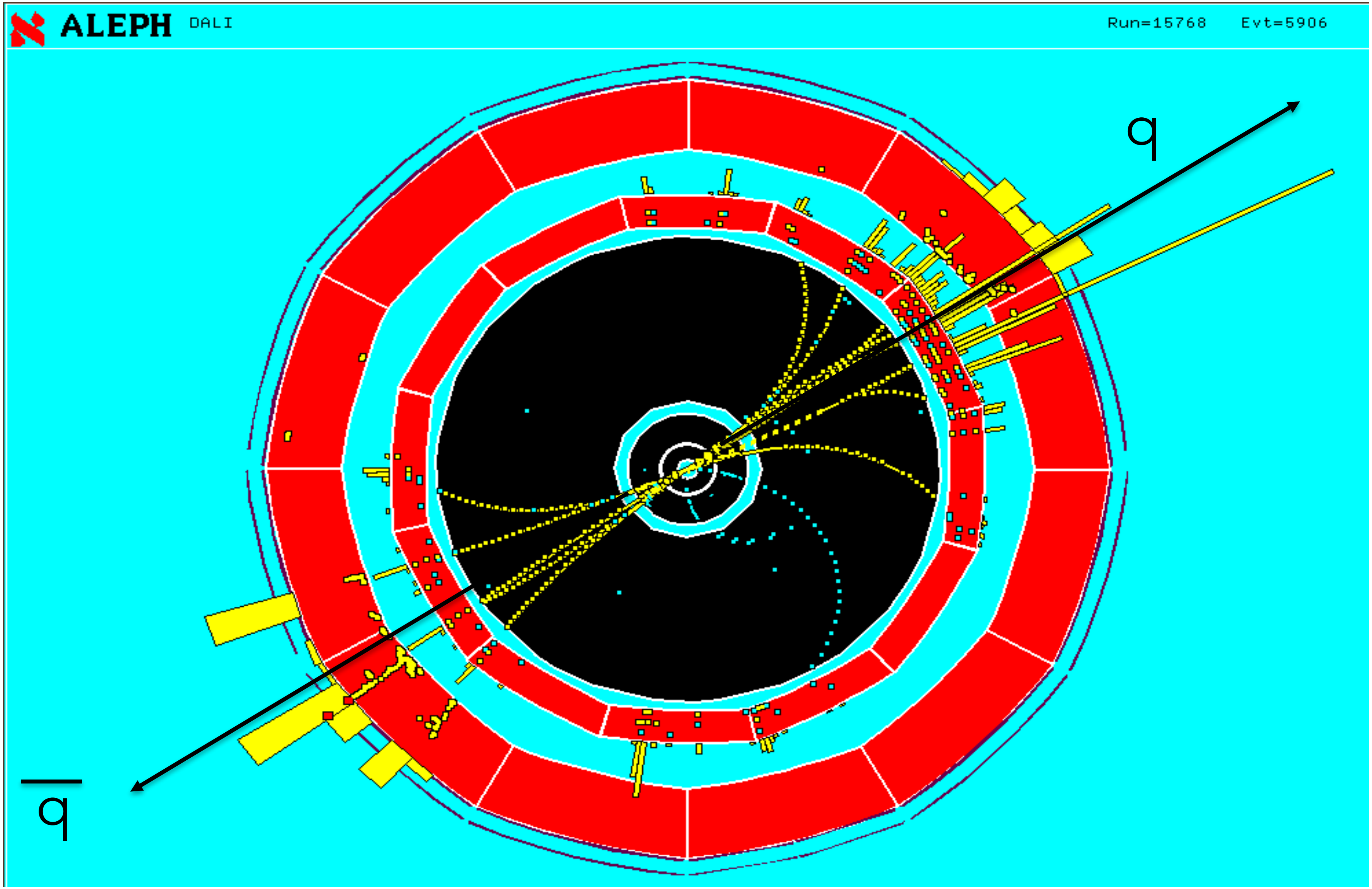
Hadronization model

$q\bar{q}$ production at LHC

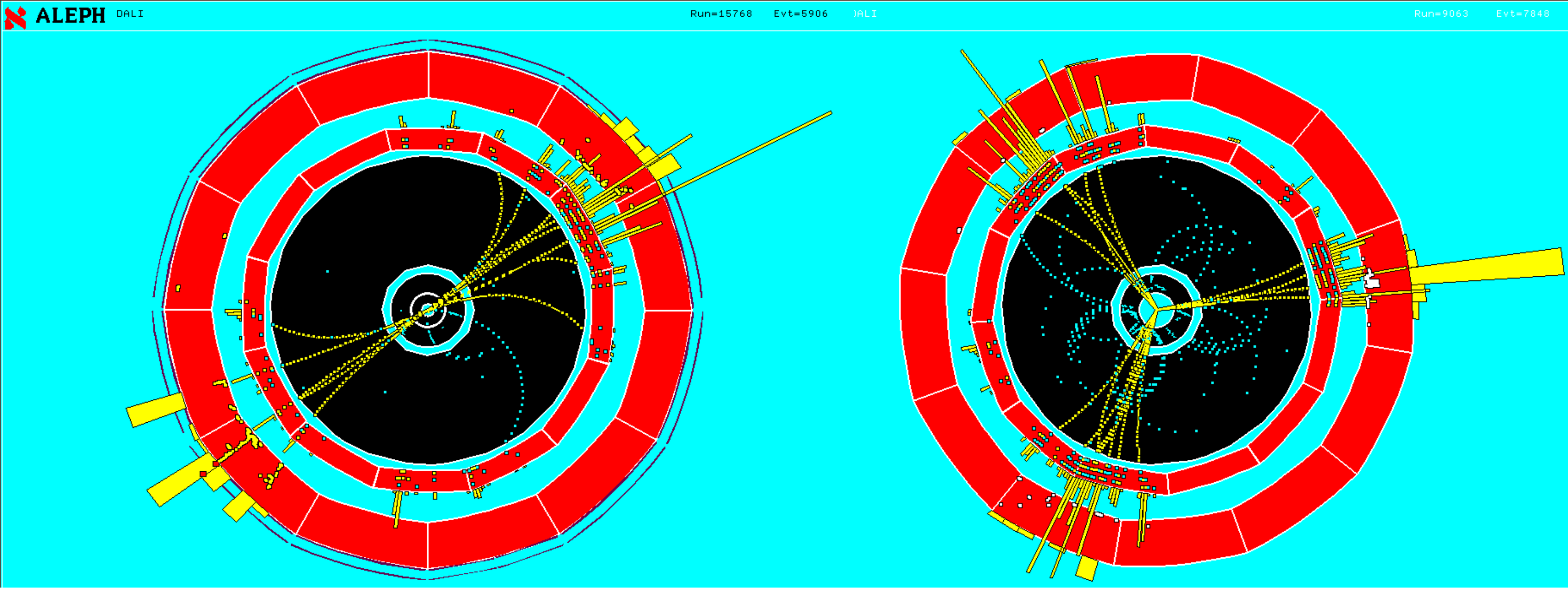


QCD (calculable)

hadronization (models needed)



LEP (~ 1990)
e+e- beams perpendicular to the page



$$R_{3/2} = \frac{\sigma_{3\ \text{jets}}}{\sigma_{2\ \text{jets}}} \sim \alpha_s$$

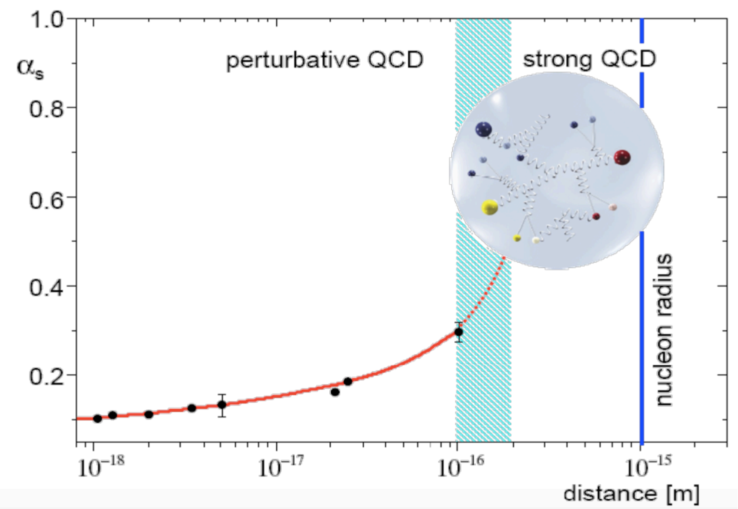
Strong interaction in summary

Very interesting *per se*

Hadrons are composed of quarks

The strong interaction charge is the « color »

The vector boson of QCD carries color
- free quarks are not observed
- asymptotic freedom
- no perturbation theory building possible at low energy → models to be developed



Has to be mastered otherwise QCD effects would shadow New Physics signs !

A very active field

Back-up slides

Differential cross section for unpolarized electron on an unpolarized nucleon :

$$\frac{d\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2}\frac{\cos^2\frac{1}{2}\theta}{\sin^4\frac{1}{2}\theta}\left[W_2 + 2W_1\tan^2\tfrac{1}{2}\theta\right]$$

W_1 and W_2 depend upon Q^2 and ν

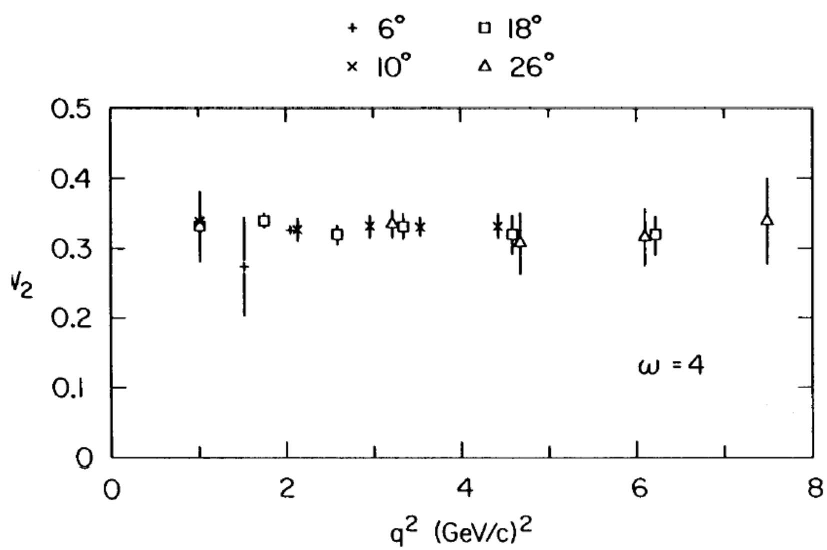
Structure functions (depend on the target properties)

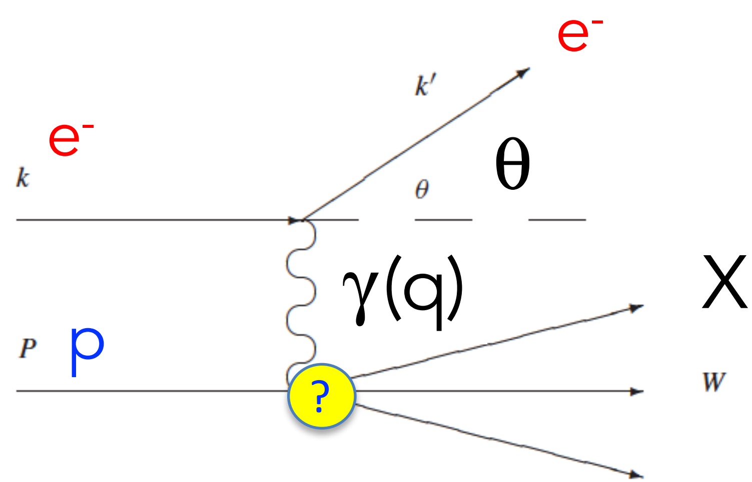
$\nu = E_i - E_f$ of the electron

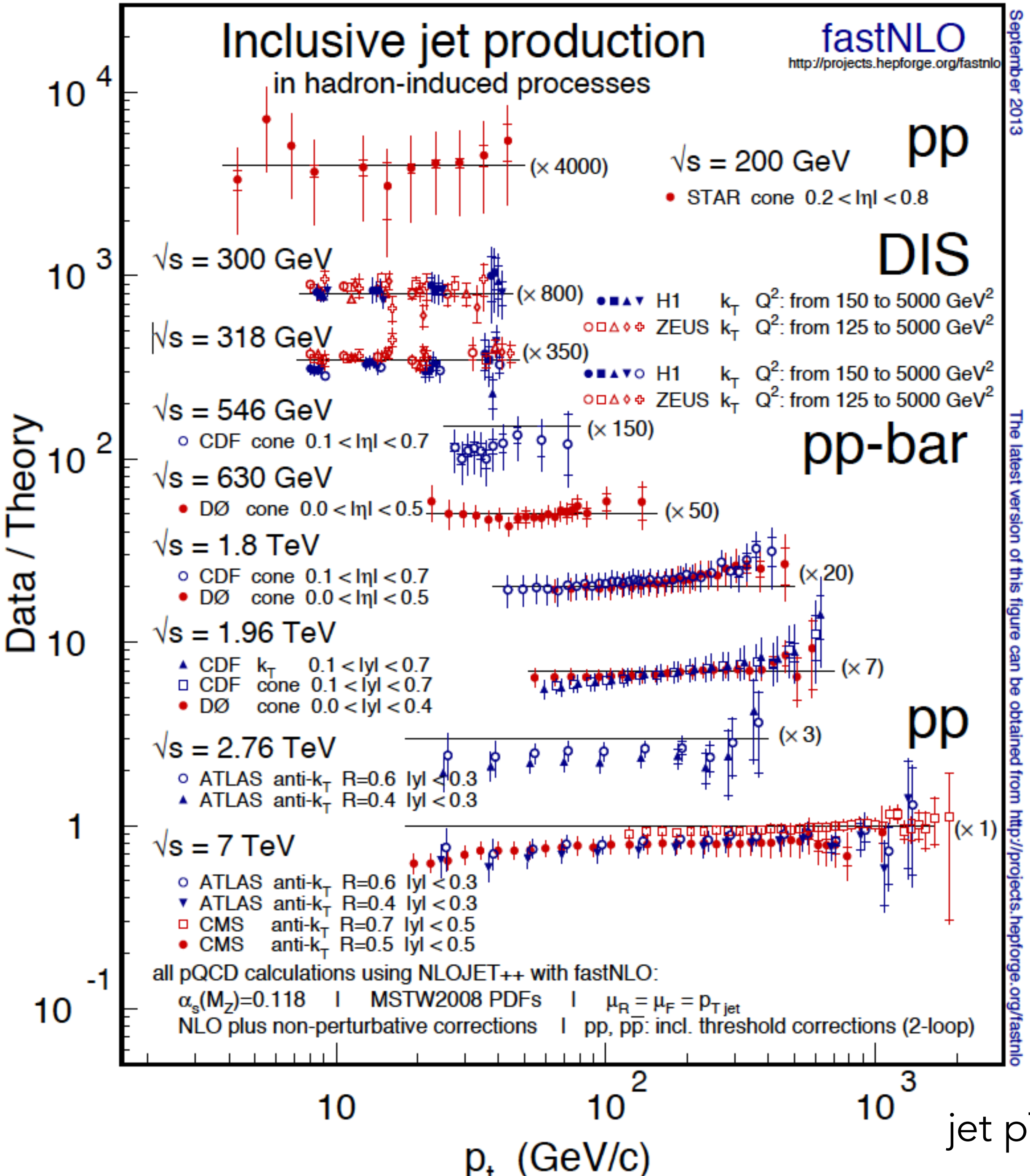
At small values of θ , study the cross section

Bjorken scaling : at high energies quarks evolve freely in the proton

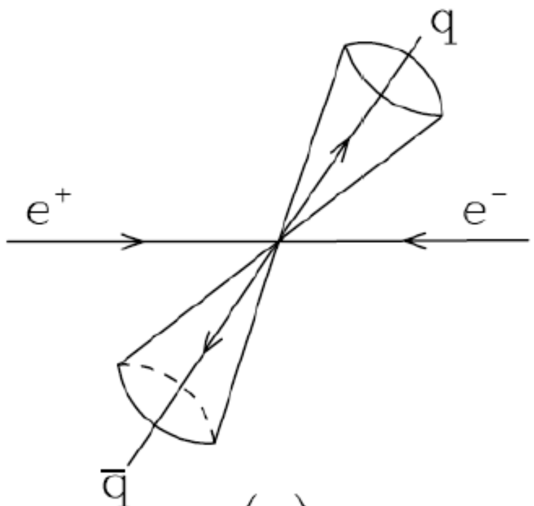
νW_2



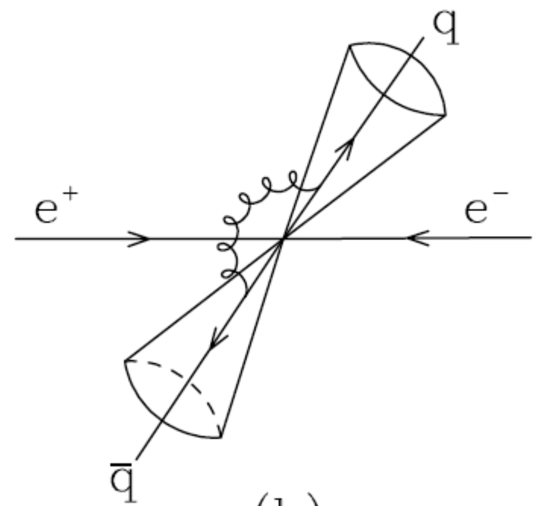



Inclusive jet production
in hadron-induced processes
fastNLO
http://projects.hepforge.org/fastnlo
September 2013
pp
√s = 200 GeV
STAR cone 0.2 < lηl < 0.8
(× 4000)
DIS
√s = 300 GeV
(× 800)
H1 k$_T$ Q^2: from 150 to 5000 GeV^2
ZEUS k$_T$ Q^2: from 125 to 5000 GeV^2
√s = 318 GeV
(× 350)
H1 k$_T$ Q^2: from 150 to 5000 GeV^2
ZEUS k$_T$ Q^2: from 125 to 5000 GeV^2
pp-bar
√s = 546 GeV
CDF cone 0.1 < lηl < 0.7
(× 150)
√s = 630 GeV
DØ cone 0.0 < lηl < 0.5
(× 50)
√s = 1.8 TeV
CDF cone 0.1 < lηl < 0.7
DØ cone 0.0 < lηl < 0.5
(× 20)
√s = 1.96 TeV
CDF k$_T$ 0.1 < lyl < 0.7
CDF cone 0.1 < lyl < 0.7
DØ cone 0.0 < lyl < 0.4
(× 7)
pp
√s = 2.76 TeV
ATLAS anti-k$_T$ R=0.6 lyl < 0.3
ATLAS anti-k$_T$ R=0.4 lyl < 0.3
(× 3)
√s = 7 TeV
ATLAS anti-k$_T$ R=0.6 lyl < 0.3
ATLAS anti-k$_T$ R=0.4 lyl < 0.3
CMS anti-k$_T$ R=0.7 lyl < 0.5
CMS anti-k$_T$ R=0.5 lyl < 0.5
(× 1)
all pQCD calculations using NLOJET++ with fastNLO:
$\alpha_s(M_Z)$=0.118 | MSTW2008 PDFs | $\mu_R = \mu_F = p_{T\,jet}$
NLO plus non-perturbative corrections | pp, p$\bar{p}$: incl. threshold corrections (2-loop)
The latest version of this figure can be obtained from http://projects.hepforge.org/fastnlo
Data / Theory
10^{-1}
1
10
10^2
10^3
10^4
10
10^2
10^3
p$_t$ (GeV/c)

jet pT

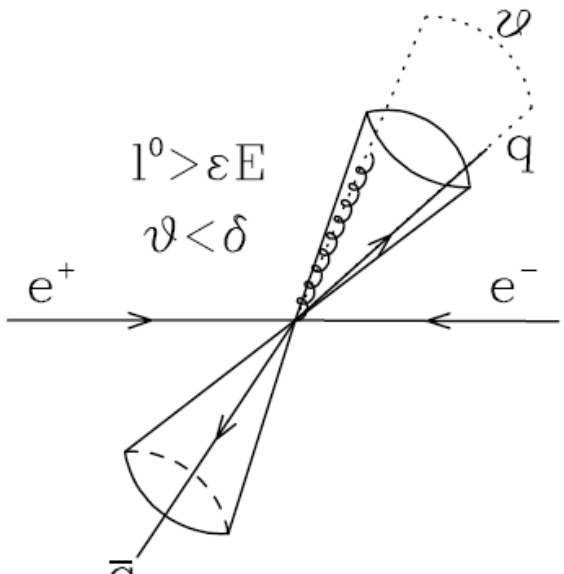


(a)

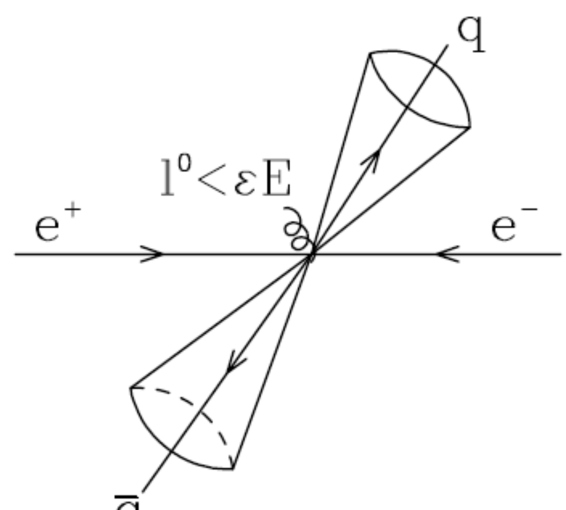


(b)

Delicate definition of what is a jet



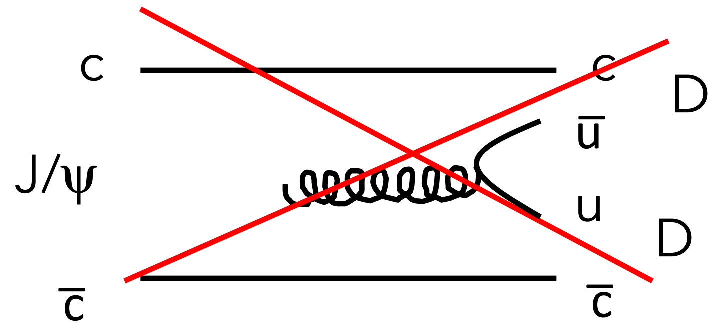
(d)



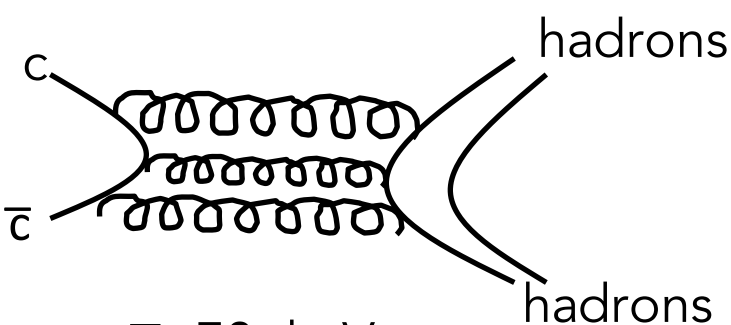
(c)

real gluon
emission

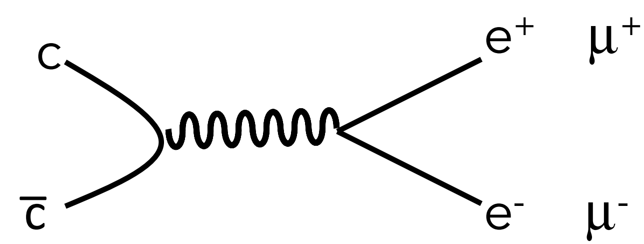
J/ψ decay :



forbidden :
$m(J/\psi) < 2\, m(D^0)$



$\Gamma \sim 70$ keV

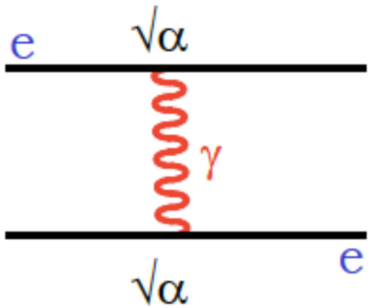


$\Gamma(ee) \sim 5$ keV
$\Gamma(\mu\mu) \sim 5$ keV

Decay through strong interaction is heavily suppressed

→ decay through QED starts to be competitive

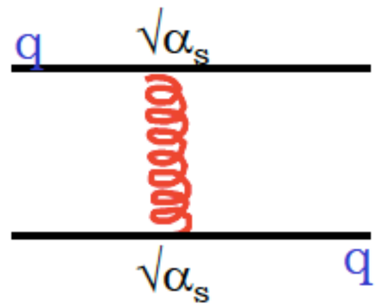
QED :

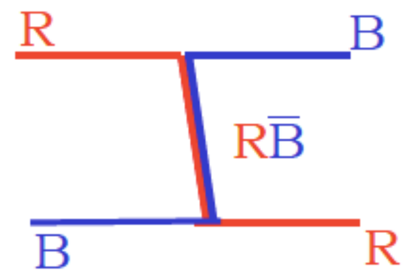


1 photon :

- massless
- electrically neutral

QCD :





8 gluons :

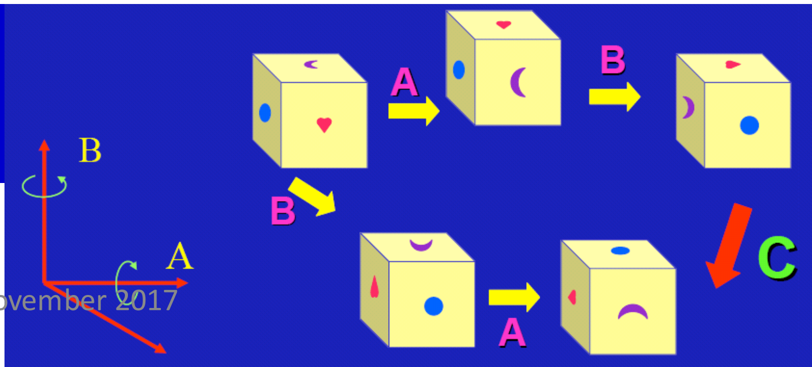
- massless
- colored

gluon self-interaction
SU(3) is a non abelian group

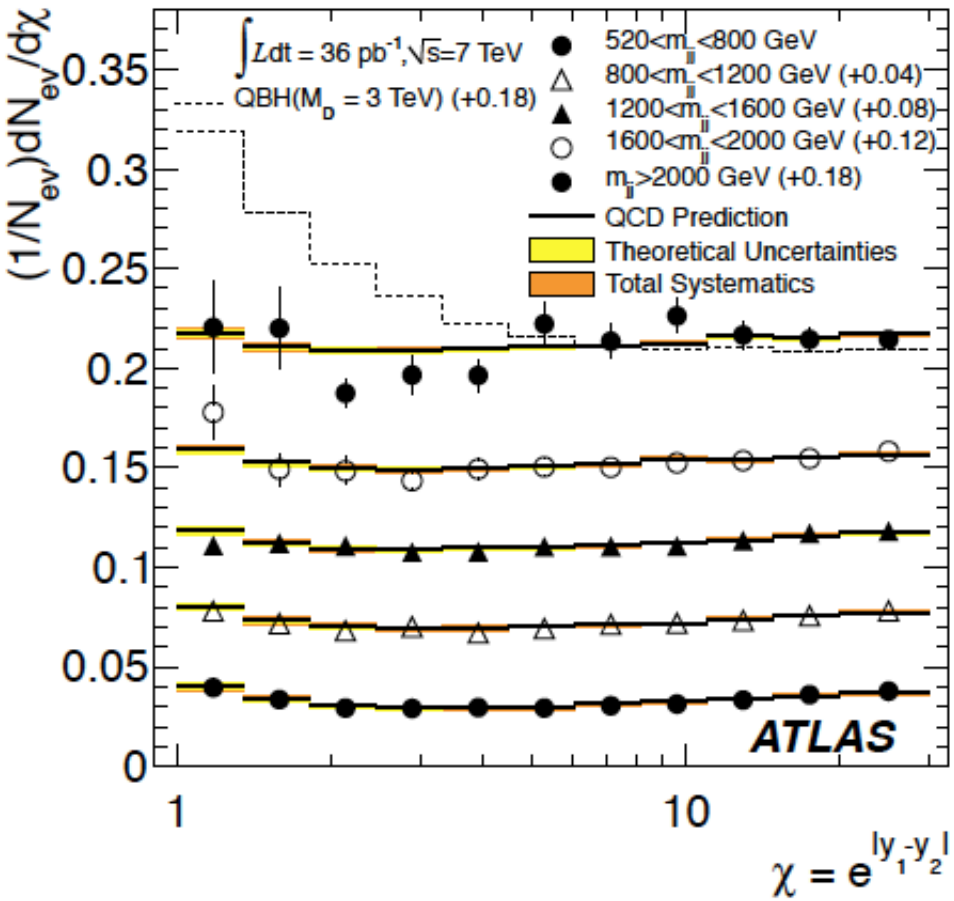
Both theories should be renormalizable

Non abelian rotation

AB-BA = C



Di-jets events at the LHC : search for NP



$$y \equiv \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$$

no …