Quarks

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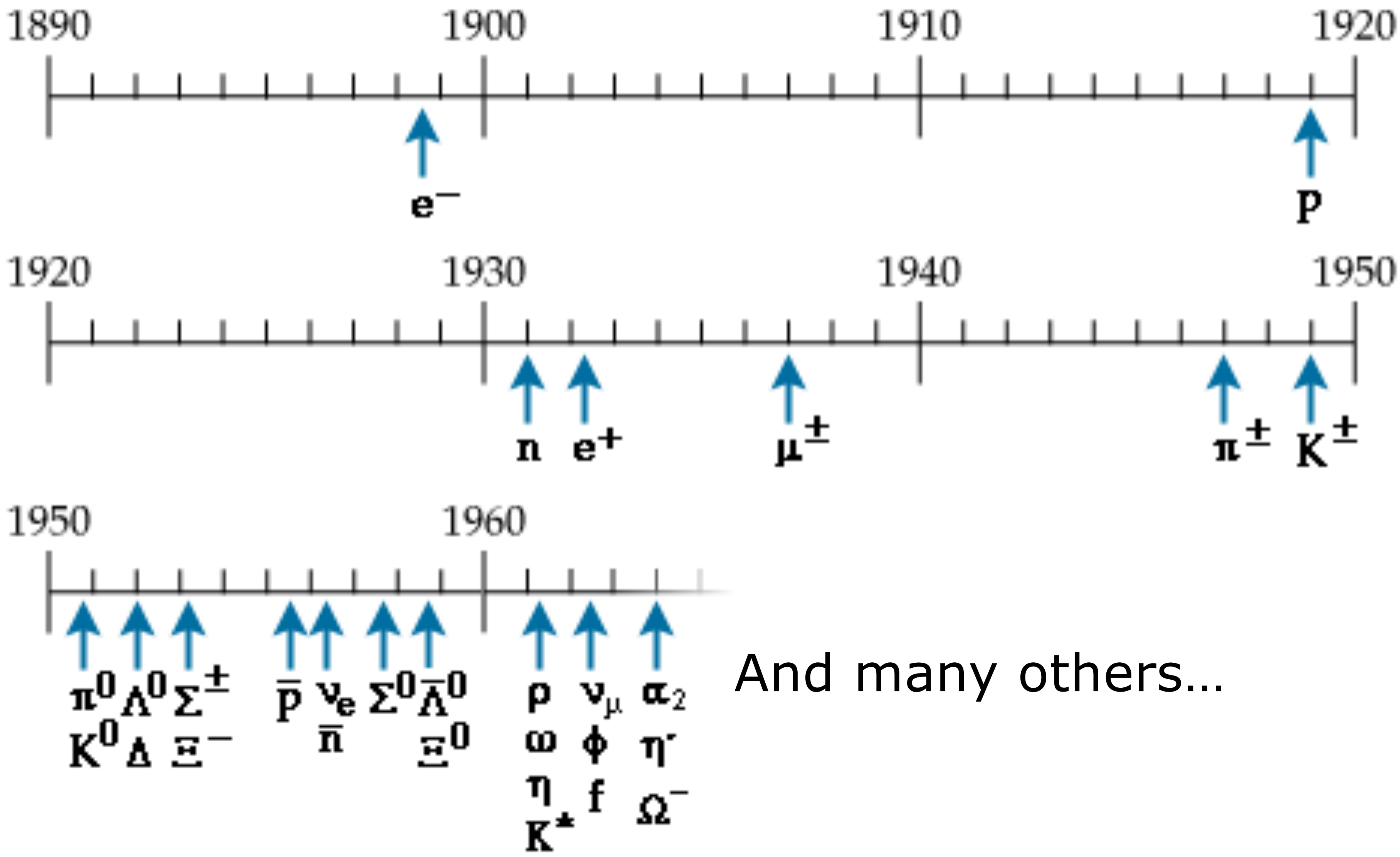
New Particles

- Collisions of elettrons and nuclea in the cosmic rays and in the particle accelerators at the beginning of the 30ies, brought to the discovery of many other particles.

- Some of them were predicted, other were discovered as surprises, being completely unexpected.

- At the beginning it was thought that all these particles were fundamentals.

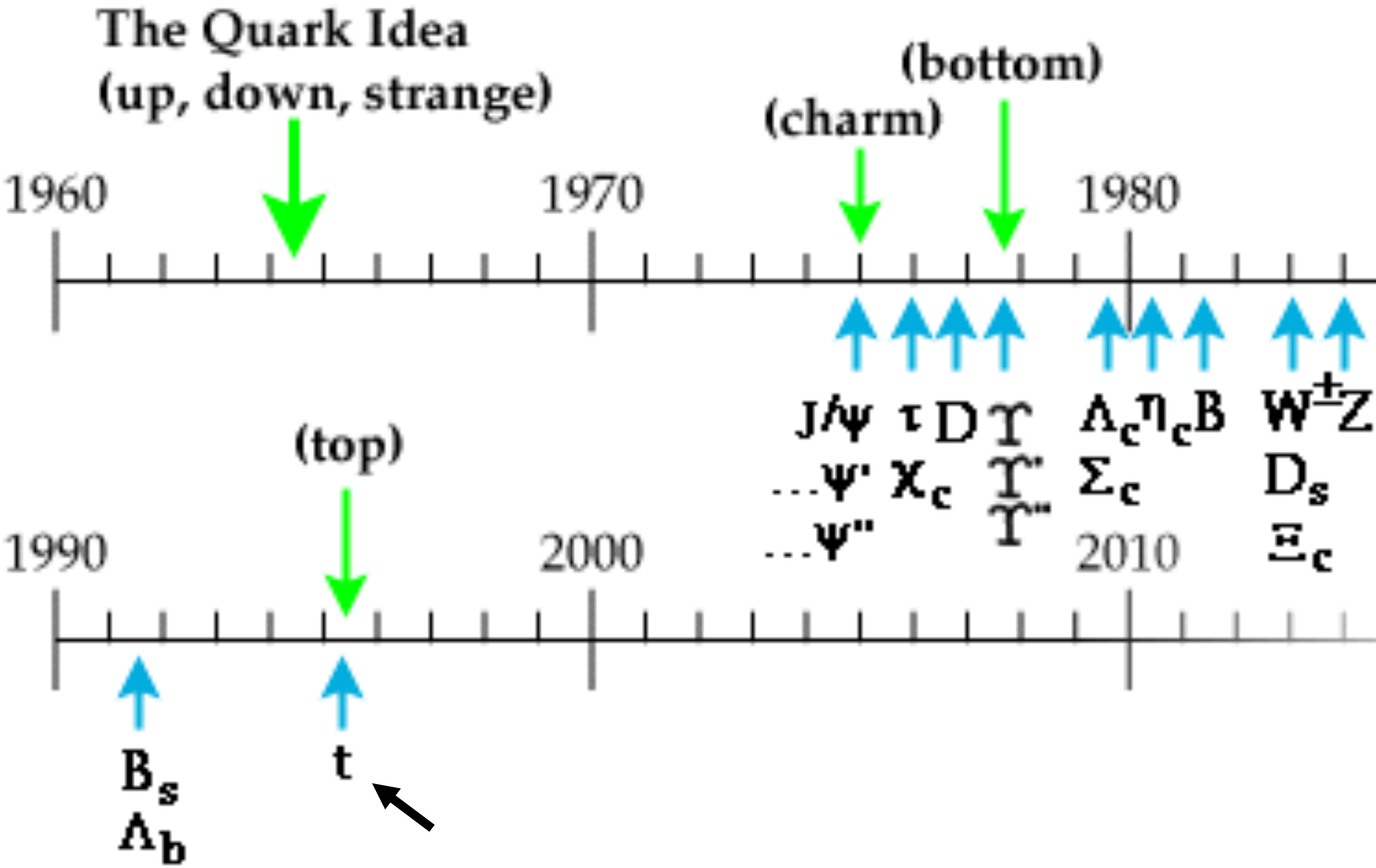
At the beginning just a few…



And many others…

The Eightfold way

- Particles, according to their properties, were grouped in multiplets. it was noticed that some members of the multiplets were missing. Because of physicists' strong belief in symmetry, experimentalists set to work to find them, a task made easier because many of the particles' properties were predicted by the theoretical model
- .
- The Ω^- was detected in 1964 at Brookhaven National Laboratory in this manner, a discovery that confirmed the usefulness of the eightfold way.


The Quark Idea
(up, down, strange)
(charm)
(bottom)
1960
1970
1980
1990
J/ψ
...ψ'
...ψ''
τ
D
χc
ϒ
ϒ'
ϒ''
Λc
ηc
B
Σc
W±Z
Ds
Ξc
(top)
1990
2000
2010
Bs
Λb
t

Quarks

- As other particles were discovered it soon became clear that the eightfold way was not the final answer. In 1963 Gell-Mann and, independently, George Zweig proposed that hadrons were formed from fractionally charged particles called *quarks*. The quark theory was unusually successful in describing properties of the particles and in understanding particle reactions and decay.
- Three quarks were proposed, named the *up* (u), *down* (d), and *strange* (s), with the charges $+2e/3$, $-e/3$, and $-e/3$, respectively. The strange quark has the strangeness value of -1, whereas the other two quarks have $S = 0$.
- Quarks are believed to be essentially pointlike, just like leptons.

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Quarks

- s = ½ fermions, subject to all kind of interactions.
- They have fractional electric charges
- Quarks and their bound states are only particles which interact strongly
- Like leptons, quarks occur in 3 generations: $\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$
- Corresponding anti-quarks are: $\begin{pmatrix} \bar{d} \\ \bar{u} \end{pmatrix} \begin{pmatrix} \bar{s} \\ \bar{c} \end{pmatrix} \begin{pmatrix} \bar{b} \\ \bar{t} \end{pmatrix}$

3 families, 6 flavours

Quark	Charge (Q/e)	Mass (GeV/c^2)
u	+2/3	~0.003
d	-1/3	~0.006
c	+2/3	~1.2
s	-1/3	~0.1
t	+2/3	~175
b	-1/3	~4.2

B = +1/3

L = 0

The quark model:

Baryons and antibaryons are bound states of **3 quarks**

Mesons are bound states of a **quark and an anti-quark**

Barions and Mesons are: **Hadrons**

Hadrons

- Quarks have never been observed as free particle
- Bound quark states are generically referred to as "hadrons"
- Two types of bound states

Historically, the existence of the hadrons and many of their properties were already known before the introduction of the so-called "static quark model" of hadrons

BARYONS $q_1 q_2 q_3$ — half-integer spin (fermions)
B = 1/3 * 3 = +1

MESONS $q_1 \bar{q}_2$ — integer spin (bosons)
B = 1/3 – 1/3 = 0

Lepton number $L_e = L_\mu = L_\tau = 0$ for all hadrons

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Quantum Numbers and flavours

- **"Strangeness"**

$$S = -[N(s) - N(\bar{s})]$$

$K^+ = u\bar{s}, K^0 = d\bar{s}$

$K^- = \bar{u}s, \bar{K}^0 = \bar{d}s$

$\Sigma^+ = uus, \Sigma^0 = uds, \Sigma^- = dds$

- **"Charm"**

$$C = N(c) - N(\bar{c})$$

$D^+ = c\bar{d}, D^0 = c\bar{u}$

$D^- = \bar{c}d, \bar{D}^0 = \bar{c}u$

- **"Beauty"**

$$\tilde{B} = -[N(b) - N(\bar{b})]$$

$B^+ = u\bar{b}, B^0 = d\bar{b}$

$B^- = \bar{u}b, \bar{B}^0 = \bar{d}b$

- **"Truth"**

$$T = N(t) - N(\bar{t})$$

No composite hadrons are formed that contain the top (anti)quark

Some examples of baryons:

Particle	Mass (Gev/c2)	Quark composition	Q (units of e)	S	C	B
p	0.938	uud	1	0	0	0
n	0.940	udd	0	0	0	0
Λ	1.116	uds	0	-1	0	0
Λ_c	2.285	udc	1	0	1	0

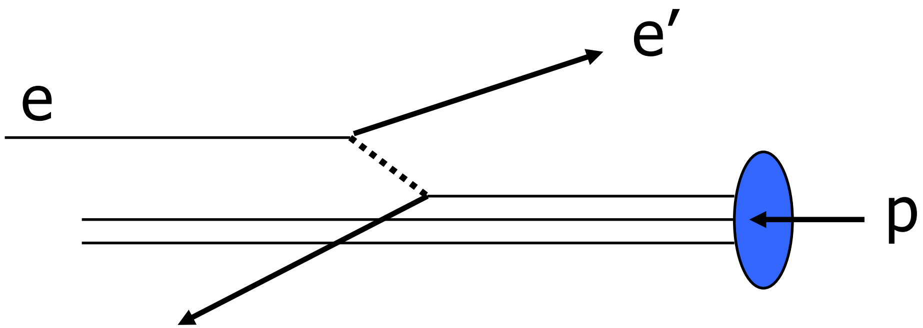
- Strangeness is defined so that S=-1 for s-quark and S =1 for the anti s-quark. Further, C=1 for c-quark, B=-1 for b-quark and T=1 for t-quark
- Since t-quark is a very short living one, there are no hadrons containing top, i,e, T=0 for all
- Quark numbers for up and down quarks have no name, but just like any other flavour, they are conserved in strong and em interactions Baryons are assigned own quantum number *B*: *B*=1 for baryons, *B*=-1 for antibaryons, *B*=0 for mesons

- Strange, charmed, bottom and top quarks each have an additional quantum number: strageness S, charm C, beauty B and truth T respectively.

- In strong interactions the flavour quantum number is conserved

- Quarks can change flavours in weak interactions ($\Delta S = \pm 1$, $\Delta C = \pm 1$)

Theory postulated in 1964 **(Gell-Mann)**



In the 70's, deep inelastic scattering of electrons on p and bound n show evidence for the quark model

Particles and Interactions

Force \ Particles	Quarks	Charged Leptons	Neutrinos
Strong	Y	N	N
Electromagnetic	Y	Y	N
Weak	Y	Y	Y

Quarks (hence hadrons) have all types of interactions!

Hadrons and lifetime

Force	Typical hadron lifetime (s)
Strong	$10^{-24} – 10^{-22}$
Electromagnetic	$10^{-21} – 10^{-16}$
Weak	$10^{-13} – 10^{-7}$

Some examples of mesons:

Particle	Mass (Gev/c2)	Quark composition	Q (units of e)	*S*	*C*	*B*
π^+	0.140	$u\bar{d}$	1	0	0	0
K^-	0.494	$s\bar{u}$	-1	-1	0	0
D^-	1.869	$d\bar{c}$	-1	0	-1	0
D_s^+	1.969	$c\bar{s}$	1	1	1	0
B^-	5.279	$b\bar{u}$	-1	0	0	-1
Υ	9.460	$b\bar{b}$	0	0	0	0

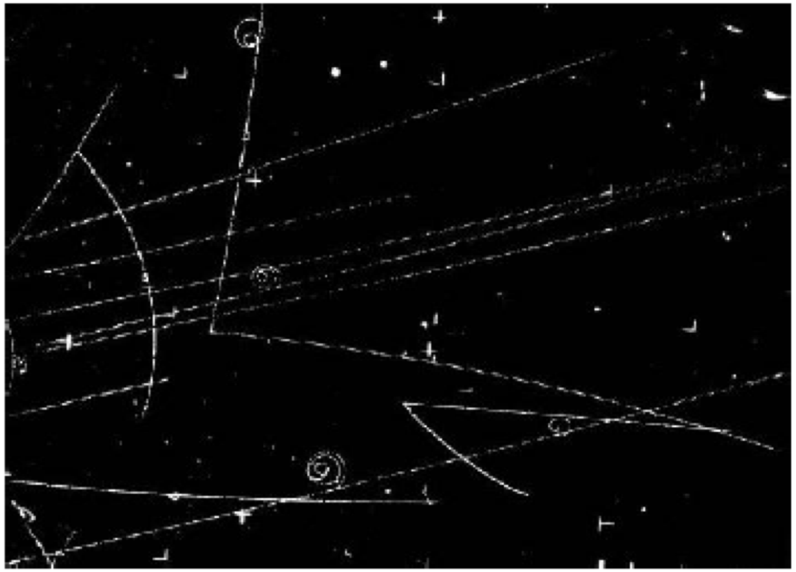
- Majority of hadrons are **unstable** and tend to **decay by strong interaction** to the state with the lowest possible mass ($\tau \sim 10^{-23}$ s)

- Hadrons with the lowest possible mass for each quark number (S, C, etc.) may live much more before decaying weekly ($\tau \sim 10^{-7}$- 10^{-13} s) or electromagnetically (mesons, $\tau \sim 10^{-16}$- 10^{-21} s)
  Such hadrons are called stable particles

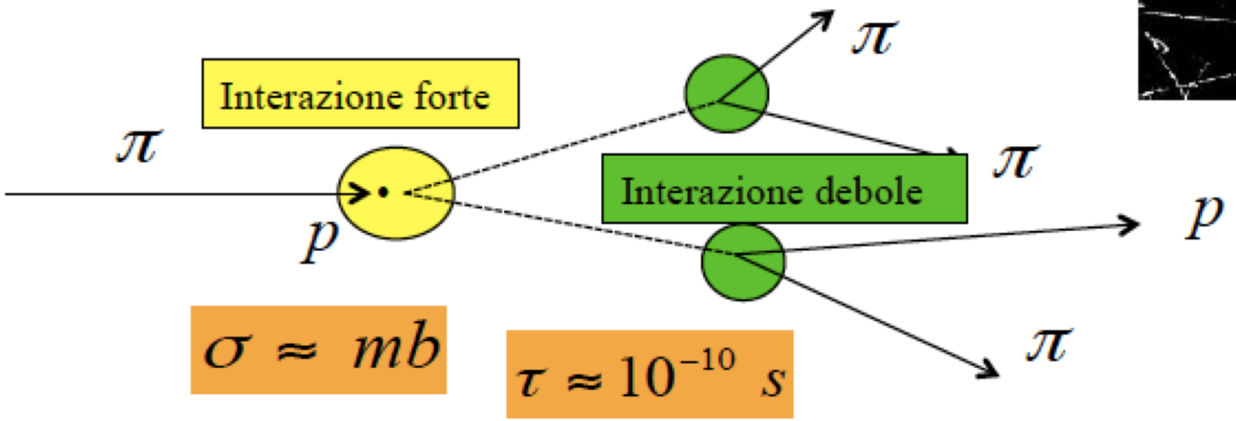
Strange particles

Presence of unknown particles in experiments with cloud chambers or emulsions on atmospheric balloons (1947, Rochester and Butler).
They turned out to be secondary particles with a characteristic “V” shape decay

$$\pi^- p \rightarrow \Lambda \overline{K} \rightarrow p \pi^- \pi^+ \pi^-$$



These particles were **produced in pairs** and characterised by:
- Strong Interaction production (cross section)
- Weak Interaction decays (lifetimes)



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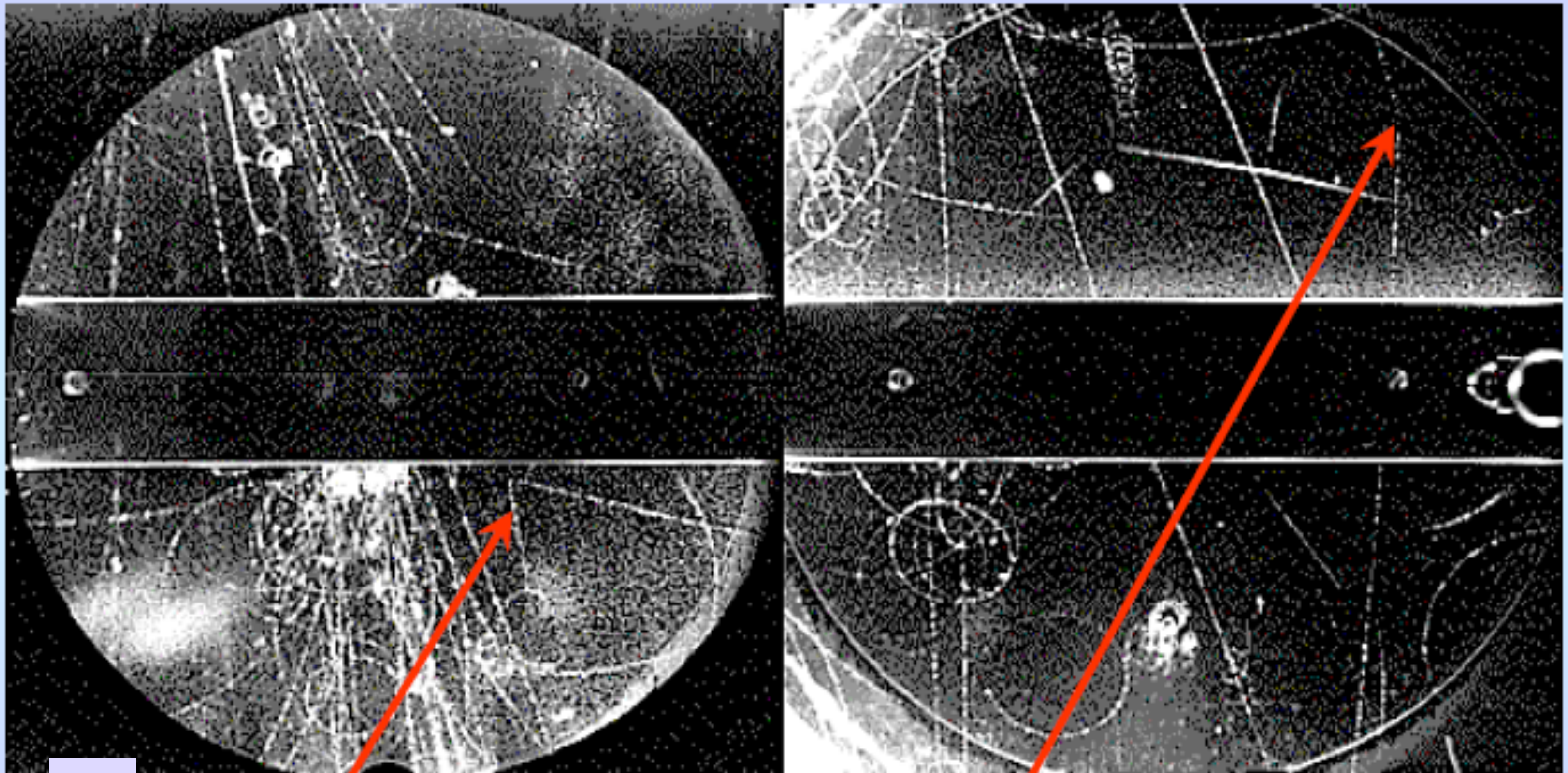
Strange particles: kaon discovery

[Rochester & Butler, 1947 (Manchester group)]



Neutral Kaon (V_0)

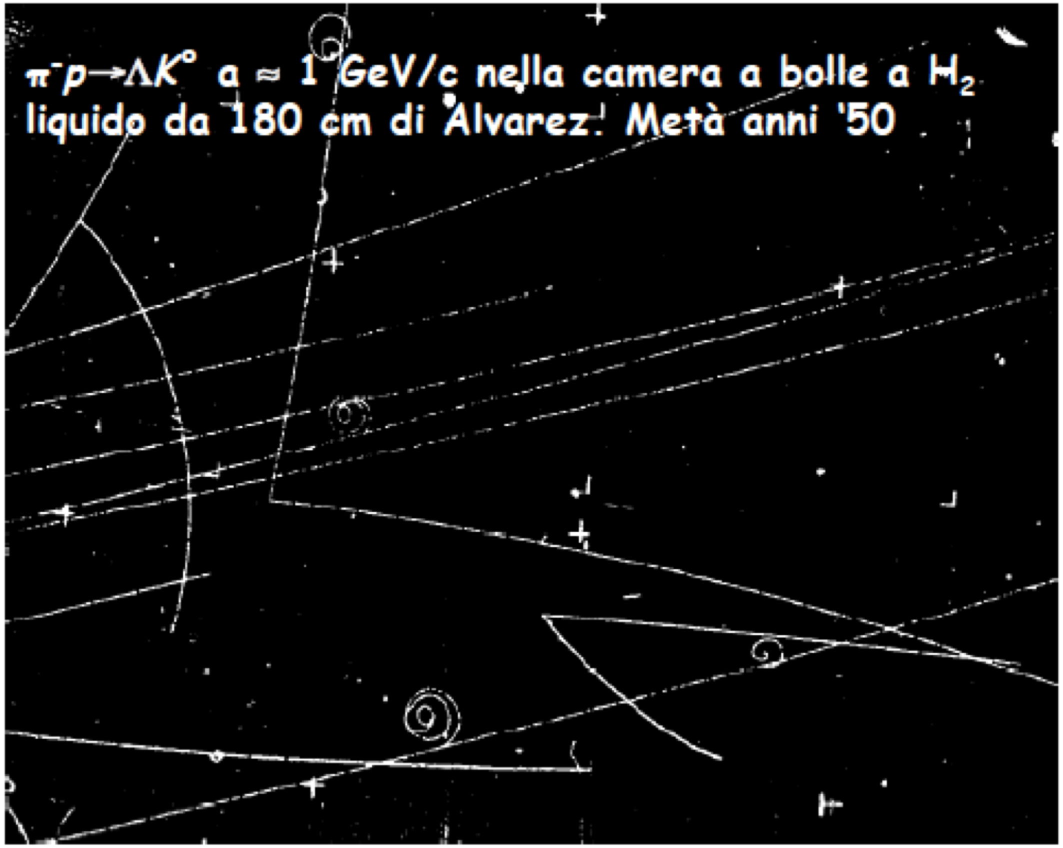
$$K^0 \rightarrow \pi^+ \pi^-$$

Charged Kaon (kink)

$$K^+ \rightarrow \mu^+ \nu_\mu$$

Weak interactions do not conserve "strangeness" S

Strange particles



Solution given by Gell-Mann (1953-56) and independently by Nisishima (1955): a new quantum number, additive, **the strangeness S**

S of the "old" particles = 0
S of strange mesons = +1
And of their anti-particles = –1
S of hyperons = – 1
And of anti-hyperons = +1

- allowed (green)
- Not allowed (red)

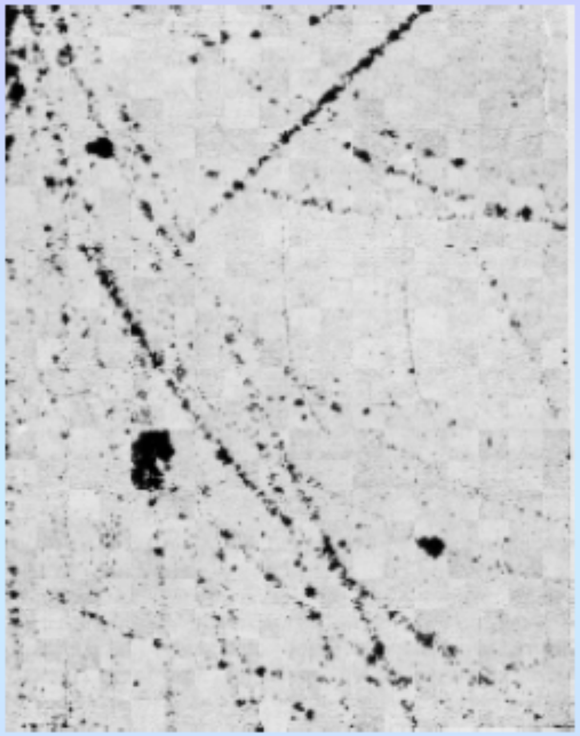
Strong interactions save S

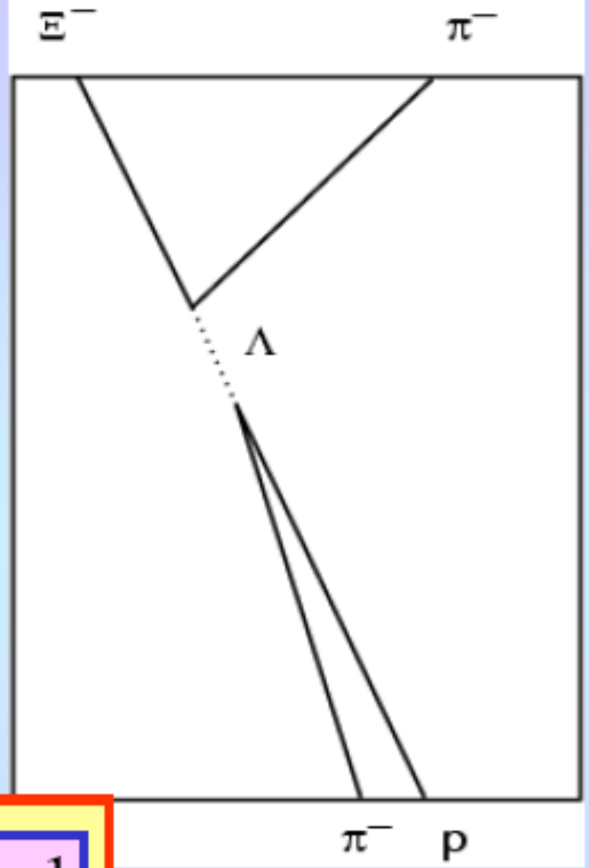
$\pi^- p \to K^0 \Lambda^0$	allowed
$\pi^- p \to K^0 n$	not allowed
$\pi^- p \to K^- \Sigma^+$	not allowed
$nn \to \Lambda\Lambda$	not allowed

Weak interactions violate S

$\Lambda \to p\pi^-$	allowed
$\Sigma^- \to n\pi^-$	allowed
$\Sigma^0 \to \Lambda\gamma$	allowed

More strange particles: S=2





$$\underset{(S=-2)}{\Xi^-} \rightarrow \underset{(S=0)}{\pi^-}\ \underset{(S=-1)}{\Lambda} \qquad \boxed{\Delta S = 1}$$

$$\mapsto \underset{(S=0)}{\pi^-}\ \underset{(S=0)}{p} \qquad \boxed{\Delta S = 1}$$

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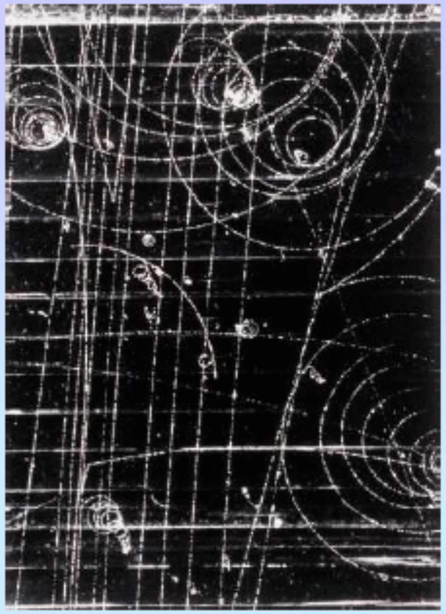
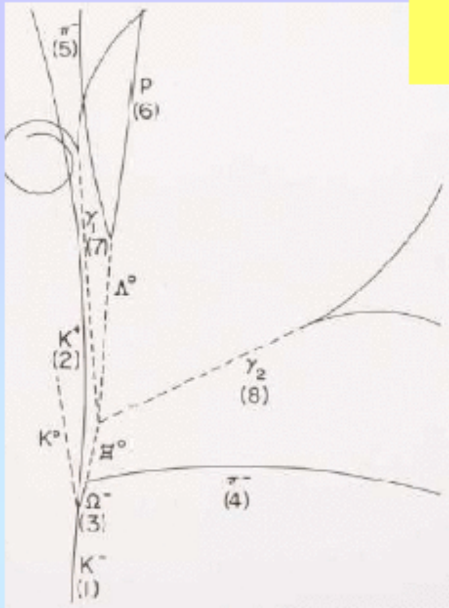
…and S = -3





Observation of Ω (=sss) a great triumph of quark model: existence predicted before its discovery in 1964!

$\Delta S = 0$ $K^- + p \to \Omega^- + K^+ + K^0$

$\Delta S = 1$ $\mapsto \Xi^0 \pi^-$

$\Delta S = 1$ $\mapsto \pi^0 \Lambda$

$\gamma\gamma \hookleftarrow$ $\mapsto \pi^- p$ $\Delta S = 1$

Strangeness conserved in strong production process but violated in weak decays

The Charm Quark

- With the u, d, s- quarks, all the known hadrons could be specified by some combination of quarks and antiquarks.
- A fourth quark called the *charmed* quark (*c*) was proposed to explain some additional discrepancies in the lifetimes of some of the known particles.
- A new quantum number called **charm *C*** was introduced so that the new quark would have $C = +1$ while its antiquark would have $C = -1$ and particles without the charmed quark have $C = 0$.
- Charm is similar to strangeness in that it is conserved in the strong and electromagnetic interactions, but not in the weak interactions. This behavior was sufficient to explain the particle lifetime difficulties.

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Heavy quarks: the charm

1974: the October revolution. J/ψ discovery in 2 experiments.

1) Brookhaven experiment: 28 GeV protons on a fixed target

$$p + Be \rightarrow J/\psi + X$$

⇓

$$e^+e^-$$

2) SLAC experiment: electron-positron collider

$$e^+e^- \rightarrow J/\psi \quad \Longrightarrow \quad e^+e^-,\ \mu^+\mu^-,\ adroni$$

⇒ Invariant mass distribution for the final states

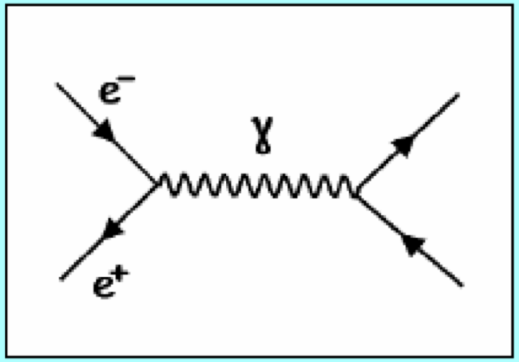
$$m^2\left(e^+e^-\right) = 2m_e^2 + 2E_1E_2 + 2p_1p_2\cos\left(\theta_1 + \theta_2\right)$$

J/Ψ and the charm quark

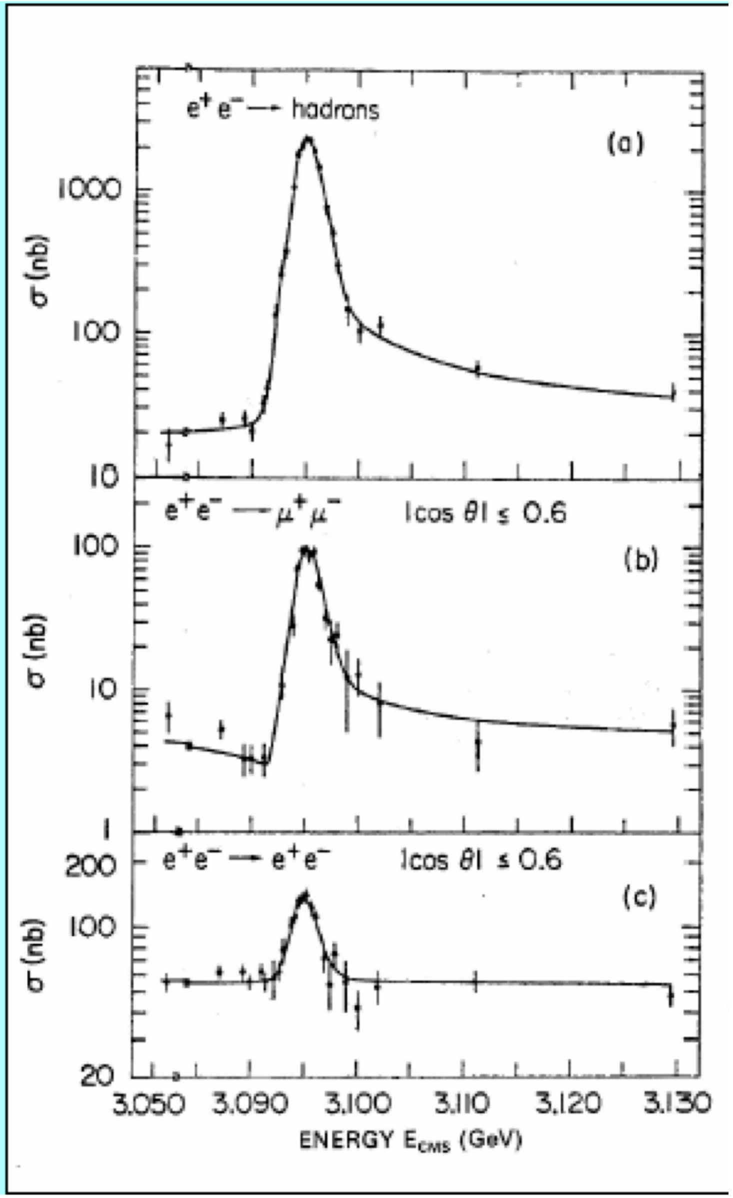
Up to 1974 there were 3 quarks u, d and s.

At SLAC (SPEAR e^+e^- Storage Ring)

$e^+ + e^- \rightarrow$ hadrons
$e^+ + e^- \rightarrow \mu^+ + \mu^-$
$e^+ + e^- \rightarrow e^+ + e^-$



Very narrow resonance (small width Γ) with a large mass of 3.1 GeV/c².

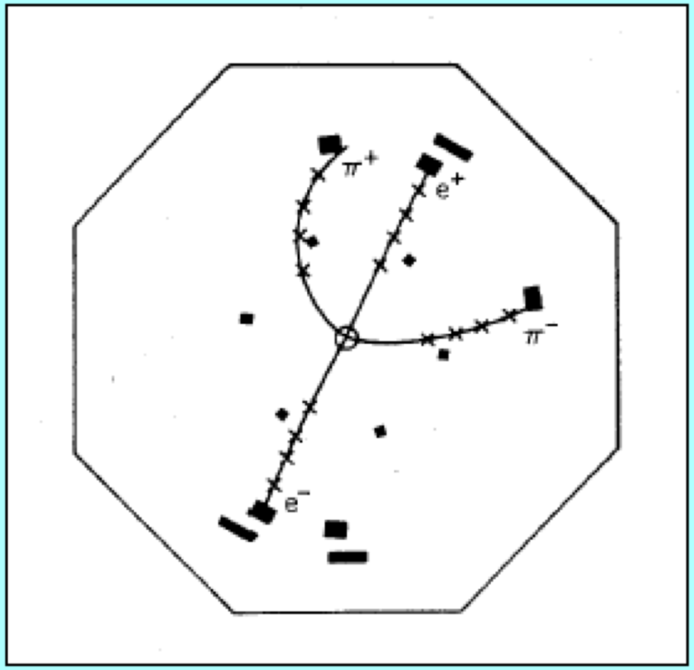


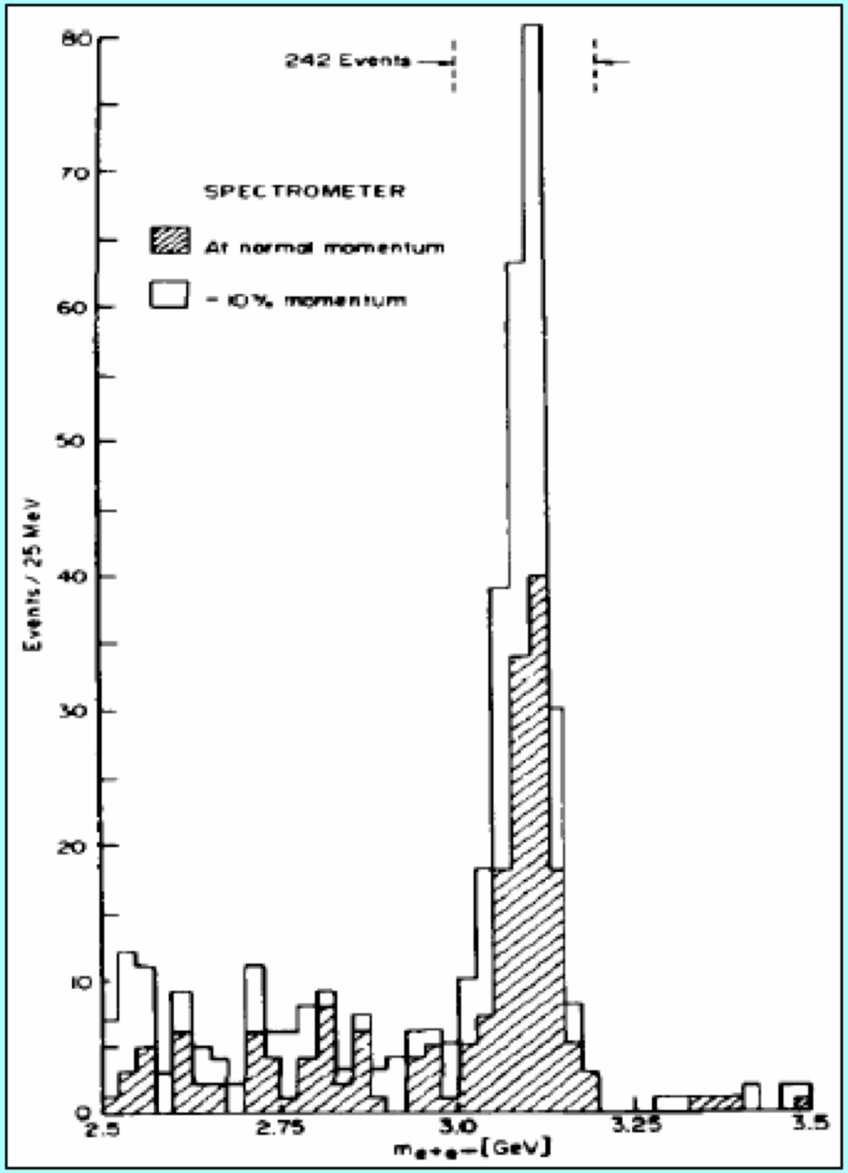
J/Ψ and the charm quark

Also at Brookhaven - 30 GeV proton synchrotron.

$$p + Be \rightarrow e^+ + e^- + anything$$

One group called it ψ - the other J - now known as J/Ψ.





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J/Ψ Width

Actual widths are smaller than observed because of measurement errors and the spread of the beam energy.

The true width $\Gamma \sim 0.067\ MeV/c^2$ - very narrow.

width $\Gamma \times$ lifetime $\tau \sim \hbar$ c.f. $\Delta E\ \Delta t \sim \hbar$

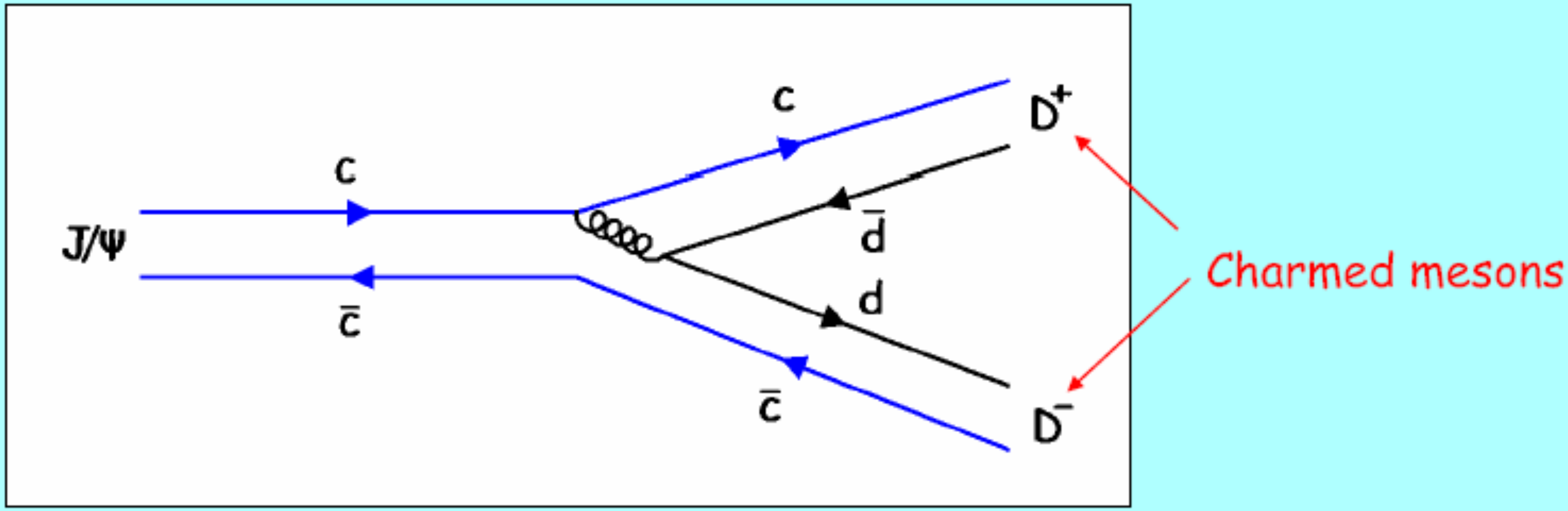
Implies long lifetime - something inhibits the decay. Would expect something this heavy to decay very rapidly to pions via Strong Interaction.

New quark flavour - charm.

Mass of charm quark $\sim 1.5\ GeV/c^2$

J/Ψ Decay

The most obvious decay of the J/ψ is a direct decay to two 'charmed' mesons, D^+ and D^-.



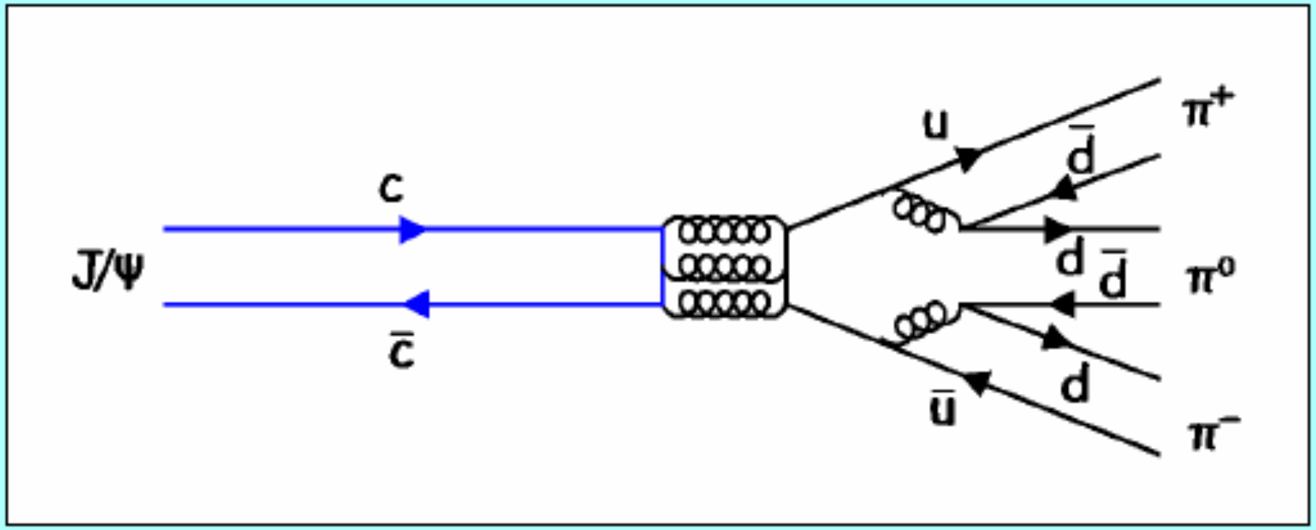
But we now know the mass of the $D^{\pm}$ is 1.87 GeV/c^2.

The mass of the J/ψ is 3.10 GeV/c^2 i.e. less than twice the $D^{\pm}$ mass.

$J/\psi \not\rightarrow D^+ + D^-$

J/Ψ Decay

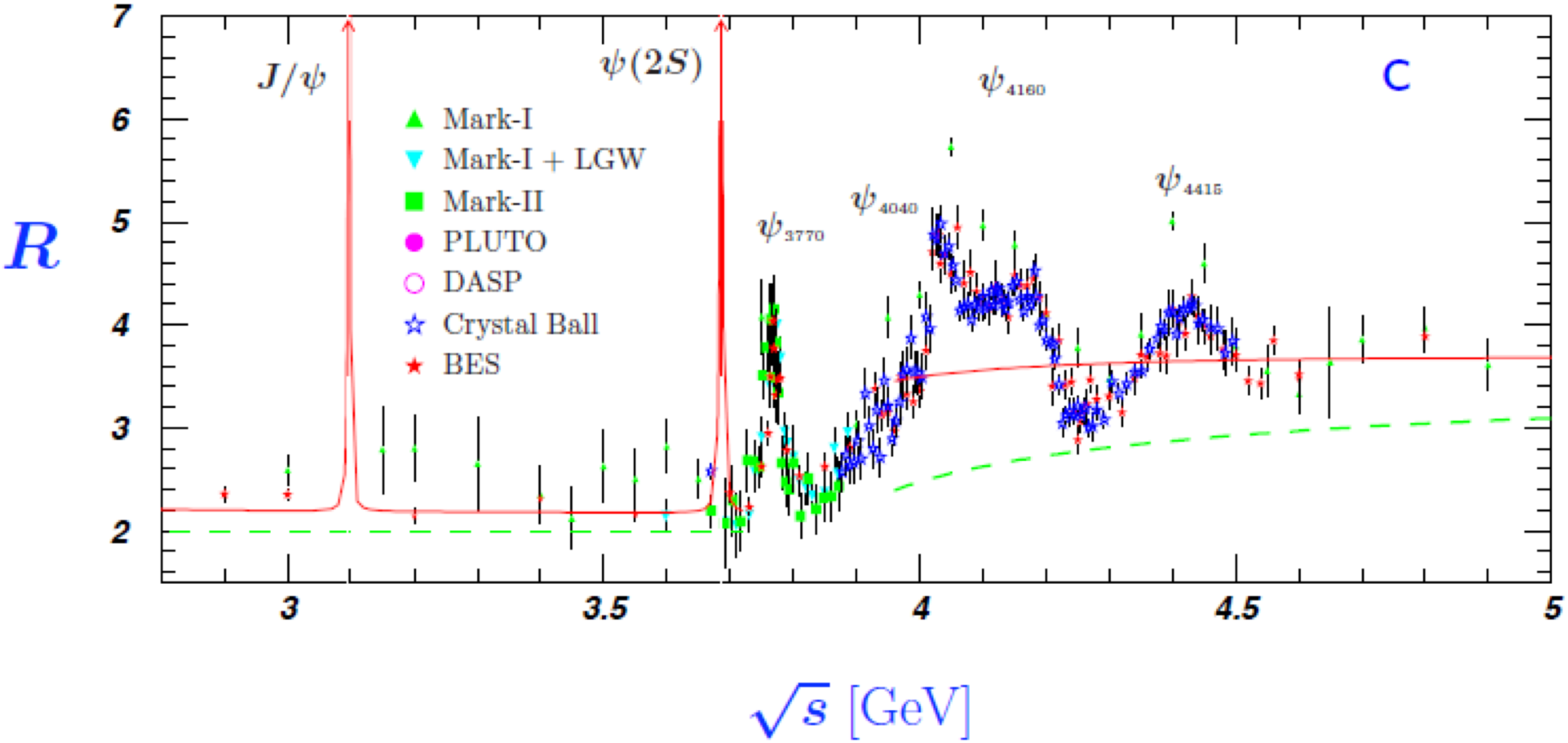
The other possibility is a 'Zweig suppressed' decay to pions.



This is inhibited by the 3 gluon coupling

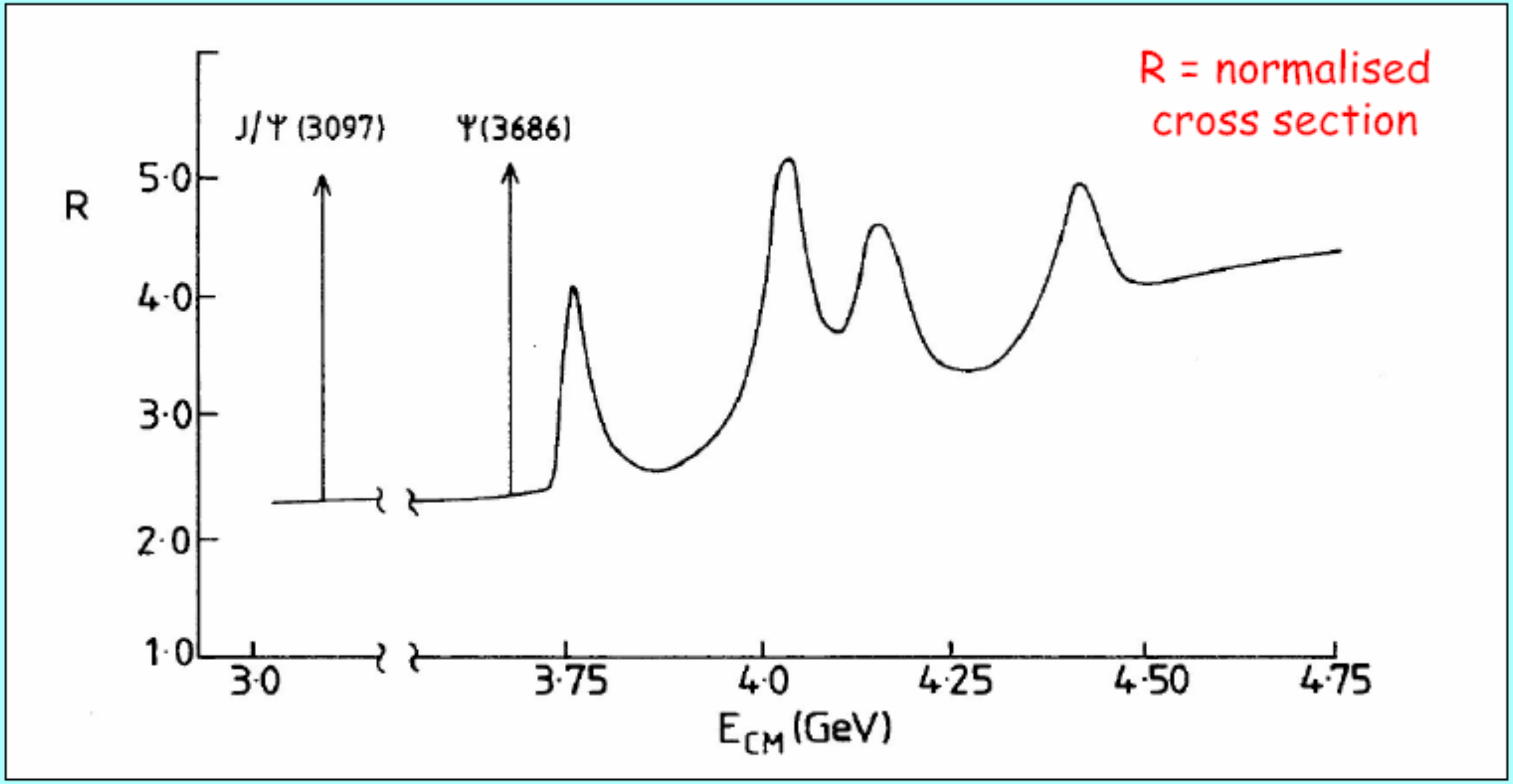
→ long lifetime → narrow width

Studying better the production region of a J/Ψ , one could notice also states of the J/ψ type much larger, over a certain threshold.



There is also a first excited state Ψ' which is also narrow.

Higher states with higher mass are wide as they can decay to $D^+ + D^-$.



Charmed Hadrons

The ($J^P = 1^-$) charmed mesons are:

$D^+ = c\bar{d}$ $\quad$ $D^- = \bar{c}d$

$D^0 = c\bar{u}$ $\quad$ $\bar{D}^0 = \bar{c}u$

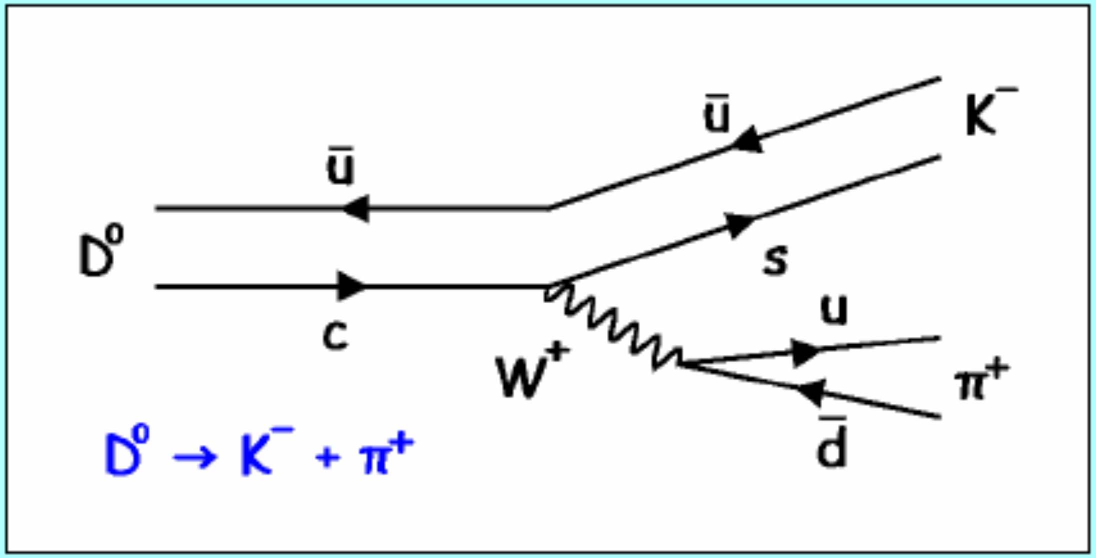
$D_s^+ = c\bar{s}$ $\quad$ $D_s^- = \bar{c}s$

Charmed baryons:

$\Lambda_c^+ = cud$ etc.

Also excited states $D^* \rightarrow D + \pi$ etc

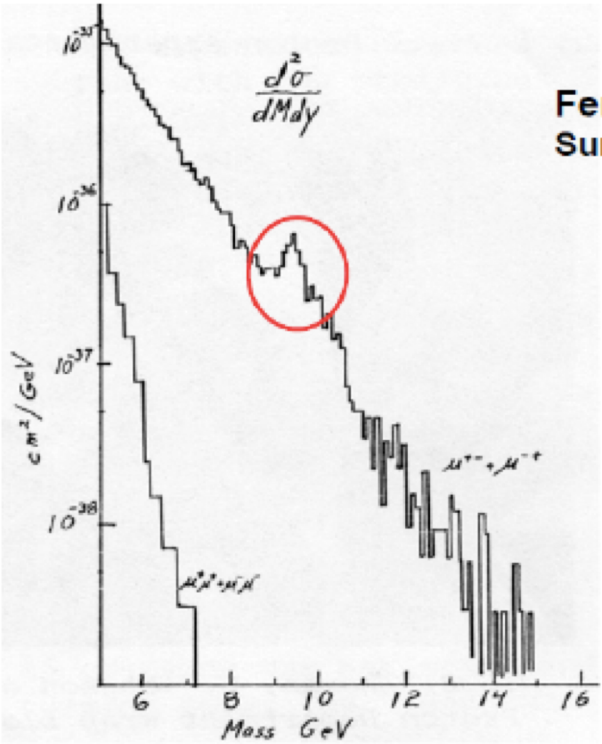
Since the charm quantum number is conserved in strong interactions, the predominant decays are via the weak interaction.



The bottom quark

Lederman et al. Experiment at Fermilab in 1977. Final state with two muons in proton (400 GeV) collision on a fixed target.

- Here's how it looked:



Fermilab
Summer, 1977

The particle discovered was

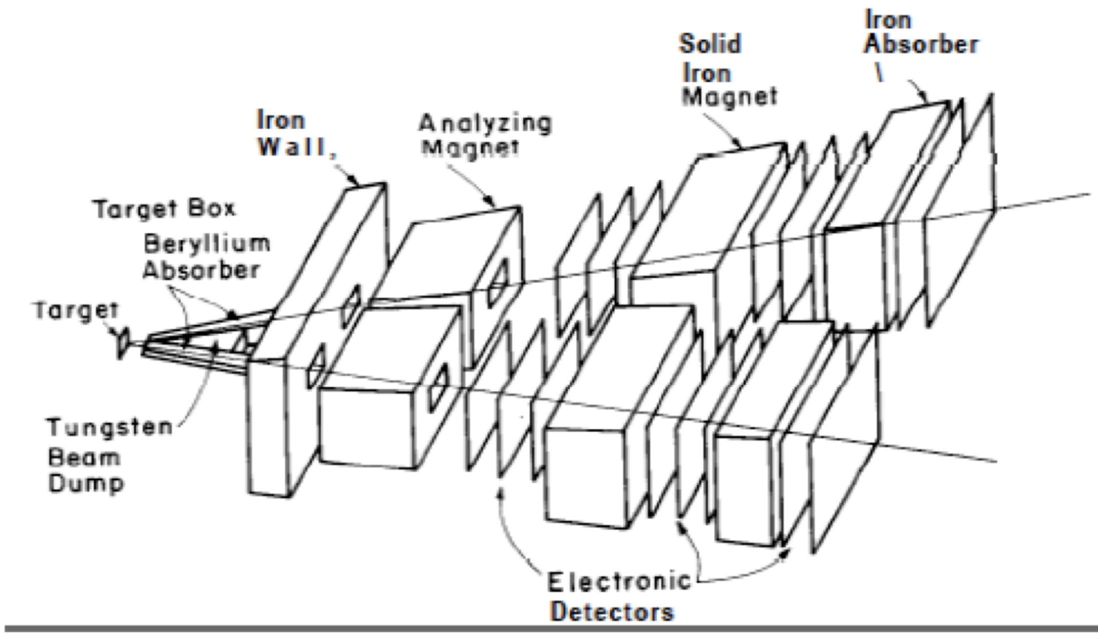
$$\Upsilon = b\bar{b},\ m = 9460,\ \Gamma = 54\ \ keV$$

In complete analogy with the J/ψ case

These particles are composed by an even heavier quark: the b-quark.

The two arms muon spectrometer

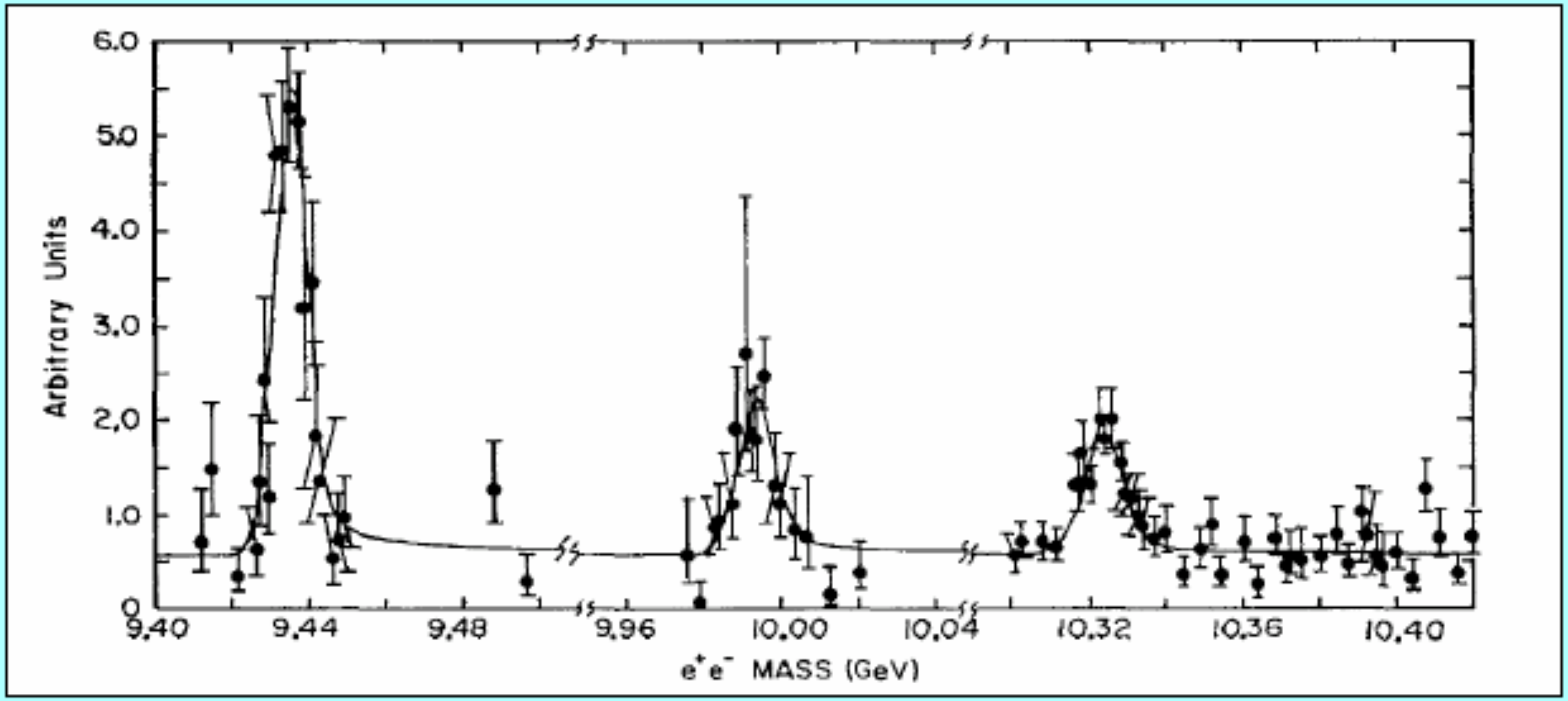
Fermilab 1977



The Upsilon

Since then precise experiments at e^+e^- machines (DORIS, Hamburg, CESR, Cornell NY).

Upsilon $\Upsilon = b\bar{b}$ Mass of b quark ~ 5 GeV/c^2.



Family of B mesons and b baryons found:

$B^+ = \bar{b}u$ $B^0 = \bar{b}d$ $B^0_s = \bar{b}s$ $\Lambda^0_b = bud$

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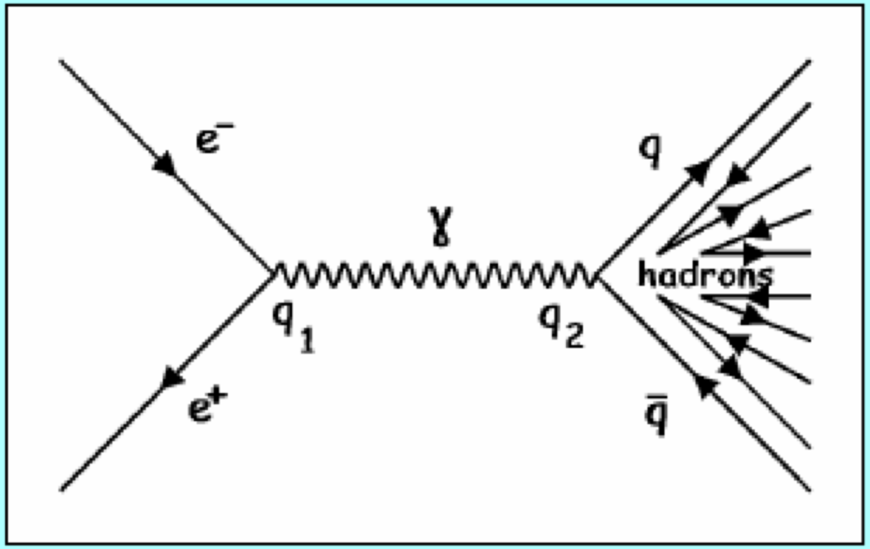
The charge of the b-quark

The charge of the b quark of $-\frac{1}{3}e$ is confirmed by measuring the ratio R:

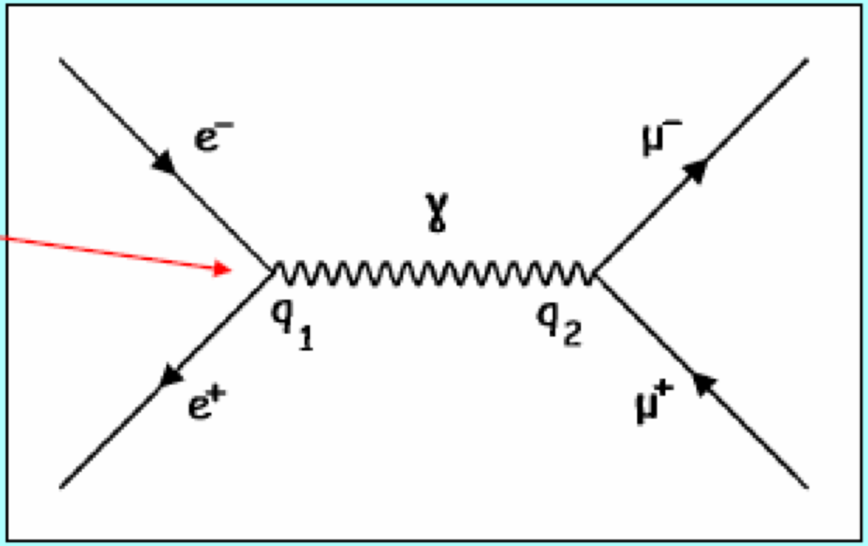
$$R = \frac{\sigma\,(e^+ + e^- \rightarrow \text{hadrons})}{\sigma\,(e^+ + e^- \rightarrow \mu^+ + \mu^-)}$$

as a function of CM (e^+e^-) energy.



The rates are determined by the strengths of the EM couplings at the two vertices given by the charges of the particles.

$$\text{Rate} \sim q_1^{\,2} \times q_2^{\,2}$$



The Top quark

After 1977 we had:

Quarks	u	c	
	d	s	b
Leptons	e	μ	τ
	ν_e	ν_μ	ν_τ

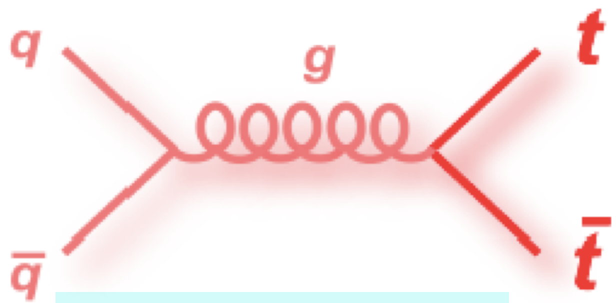
Obviously one missing 'top' t

Also good theoretical reasons for complete 'doublets'.

Searched in vain at e^+e^- machines, PETRA, PEP, LEP etc - ruling out any new quarks at their energies → top mass > 45 GeV/c^2 (half LEP1 energy).

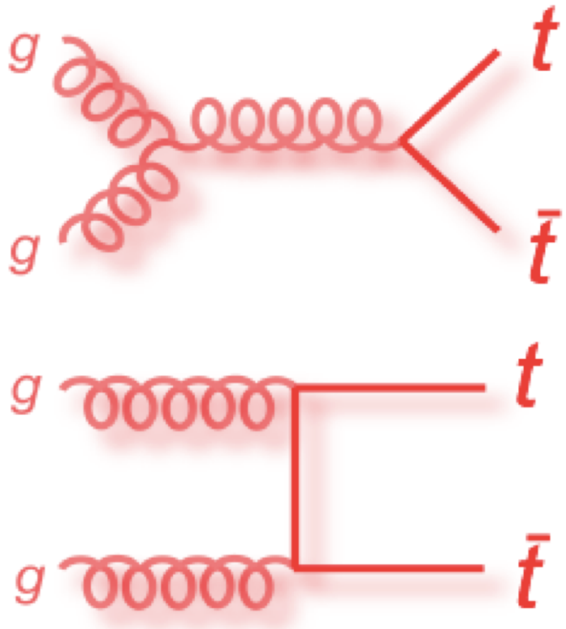
The Top quark discovery

The sixth quark was found in 1994 at Fermilab. The first evidence came from the CDF experiment in proton/antiproton collisions at the energy of 1.8 TeV.

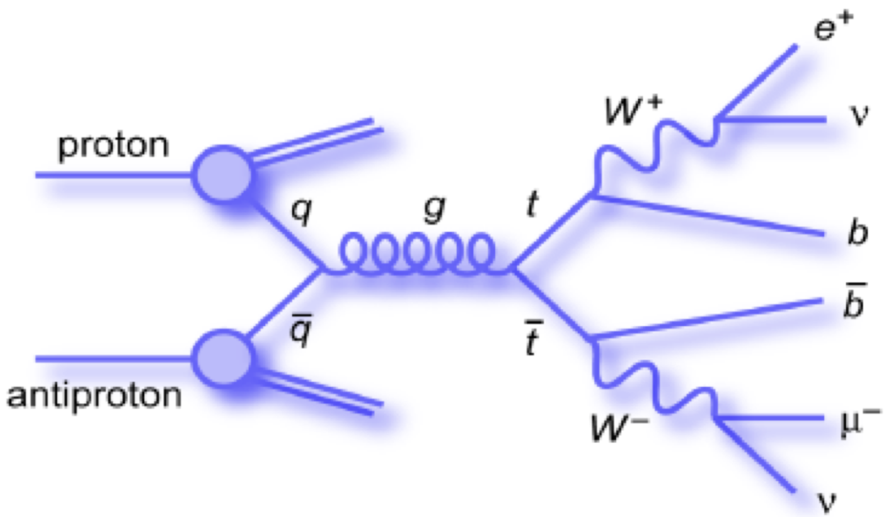


Quark annihilation

Gluon-gluon fusion



Typical Feynman diagrams for production



Topology of a top event

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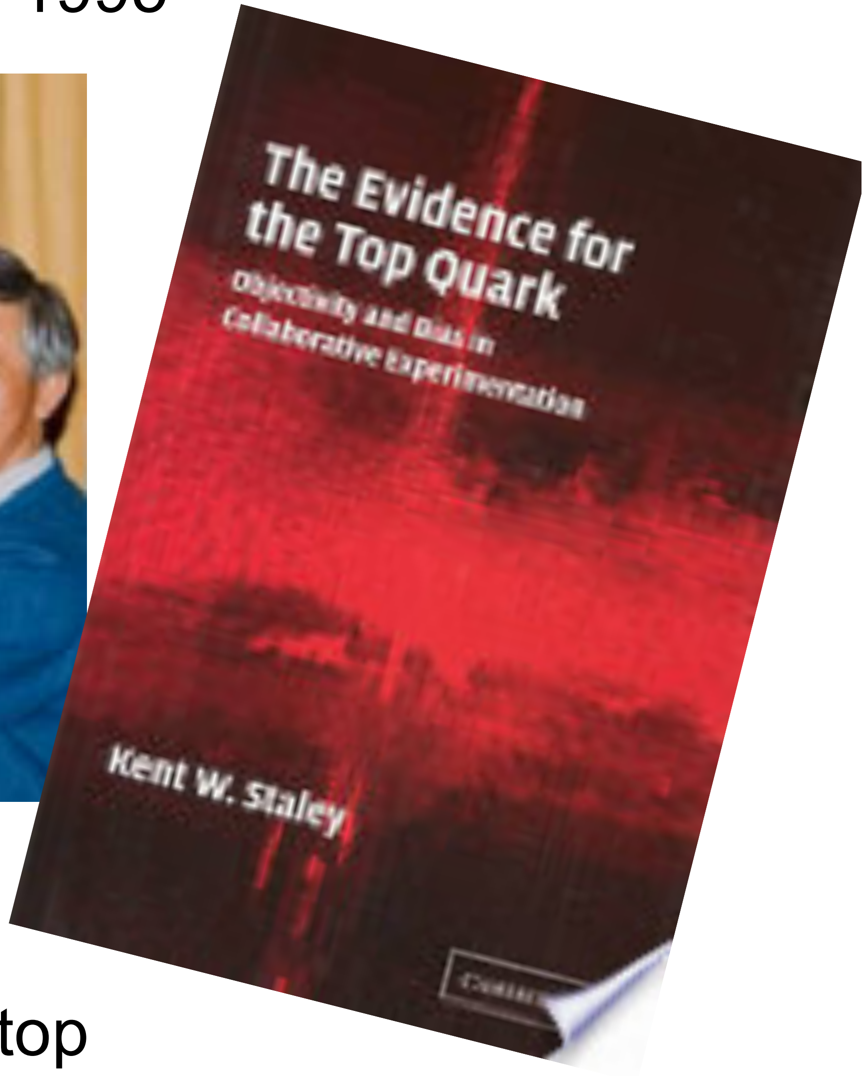
Moriond Conference

France 1995



The full story of top discovery in two books!

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Virgin Islands Summer School

US 1994

很快见到你