II. The Quark Sector

1. Experimental foundations of the quark structure

1.1 “Early History”

- Proton (p) and electron (e) were known before 1930
- Neutron (n) was discovered by J. Chadwick in 1932: “neutral proton”
- Positron was discovered in 1933 in cosmic rays by Anderson
- Muon and charged pion were discovered in cosmic rays in 1930s/1940s
- Strange particles were discovered in cosmic rays 1947

With the advent of particle accelerators a new source of particles was available:

- Neutral pion discovered in 1950 by Panofsky and Steinberger.
- In the following years (1952 – 1964) a plethora of new unstable “resonances“ and quasi-stable particles were discovered.
- At the same time the “strong isospin” concept was introduced:

$$p \leftrightarrow n: \; I = \tfrac{1}{2}, I_3 = \pm\tfrac{1}{2}$$

$$\pi^+ \leftrightarrow \pi^0 \leftrightarrow \pi^- : \; I = 1, I_3 = 0, \pm 1$$

1.2 Discovery of “strange” particles

Kaons: $K^+(u\bar{s}) \quad K^-(\bar{u}s)$ $\qquad m_{K^\pm} = 494\,\text{MeV} \quad \tau_{K^\pm} = 12.4\,\mu s$

$$\underbrace{K^0(d\bar{s}) \quad \bar{K}^0(\bar{d}s)}_{K_S^0 \quad K_L^0}$$

$$m_{K^0} = 498\,\text{MeV}$$

$$\tau_{K_s} = 90\,\text{ps} \qquad \tau_{K_L} \approx 52\,\text{ns}$$

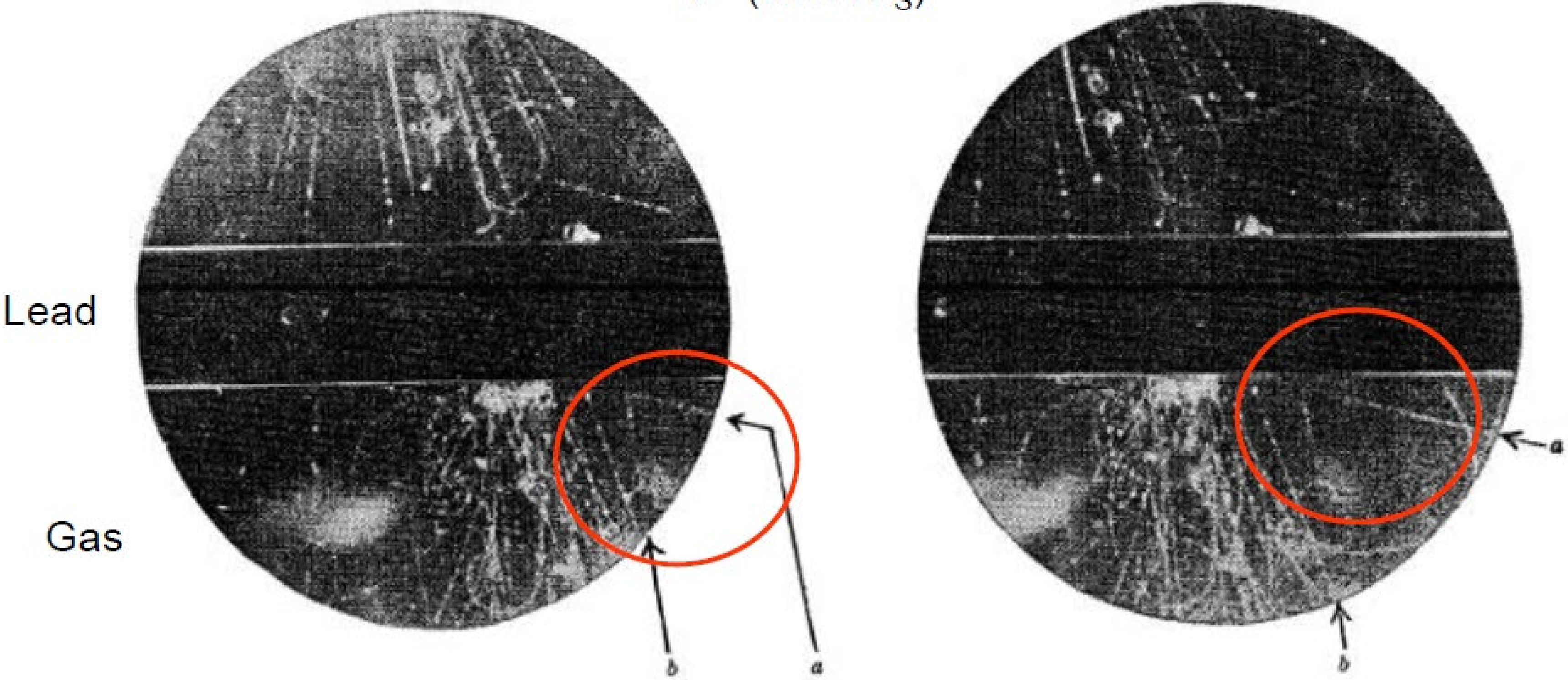
History of kaons physics is very rich. Ground breaking discoveries:
New quantum number (strangeness) → quark model;
mixing & regeneration, CP violation.

1947: Rochester & Butler

Discovery of the V_0 (K_s) particle in a cosmic ray shower provoked by a lead target in a cloud chamber: observation of long-lived neutral particles, decaying into 2 tracks with a “very striking” character (V-shape).

Discovery of the K_s

V^0 (now K^0_S)

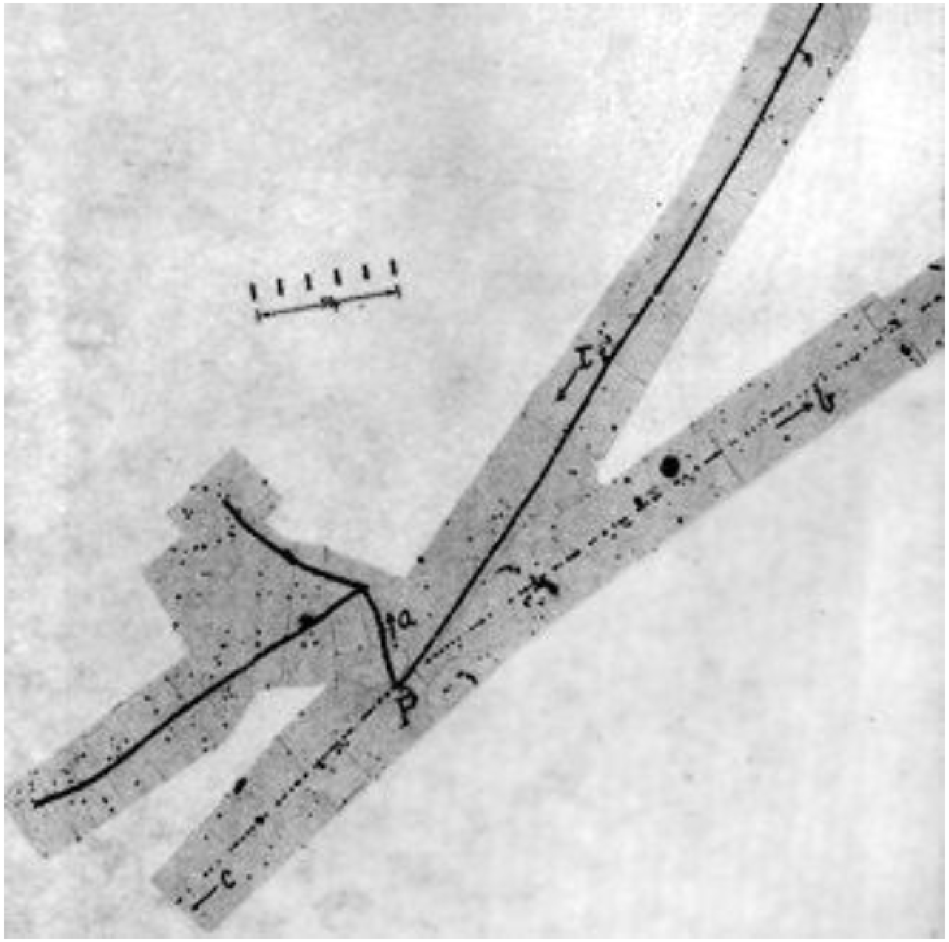


Rochester & Butler, 1947 in a cloud chamber exposed to **cosmic rays**

“ Forked tracks of a very striking character “

A large number of subsequent cosmic ray experiments lead to the discovery of further “unstable particles” with typical lifetimes of 10^{-9}… 10^{-10} s.

e.g. R. Brown et al. $\tau^{+}\,(K^{+}) \rightarrow \pi^{+}\,\pi^{-}\,\pi^{+}$



Emulsion technique, Bristol group, 1949

Old Name	New Name
τ	$K^{+} \rightarrow \pi^{+}\pi^{+}\pi^{-}$
V_1^{0}	$\Lambda^{0} \rightarrow p\pi^{-}$
V_2^{0} (θ^{0})	$K^{0}_{S} \rightarrow \pi^{+}\pi^{-}$
κ	$K^{+} \rightarrow \mu^{+}\nu$
	$K^{+} \rightarrow \mu^{+}\pi^{0}\nu$
χ (θ^{+})	$K^{+} \rightarrow \pi^{+}\pi^{0}$
V^{+}, Λ^{+}	$\Sigma^{+} \rightarrow p\pi^{0}$, $n\pi^{+}$

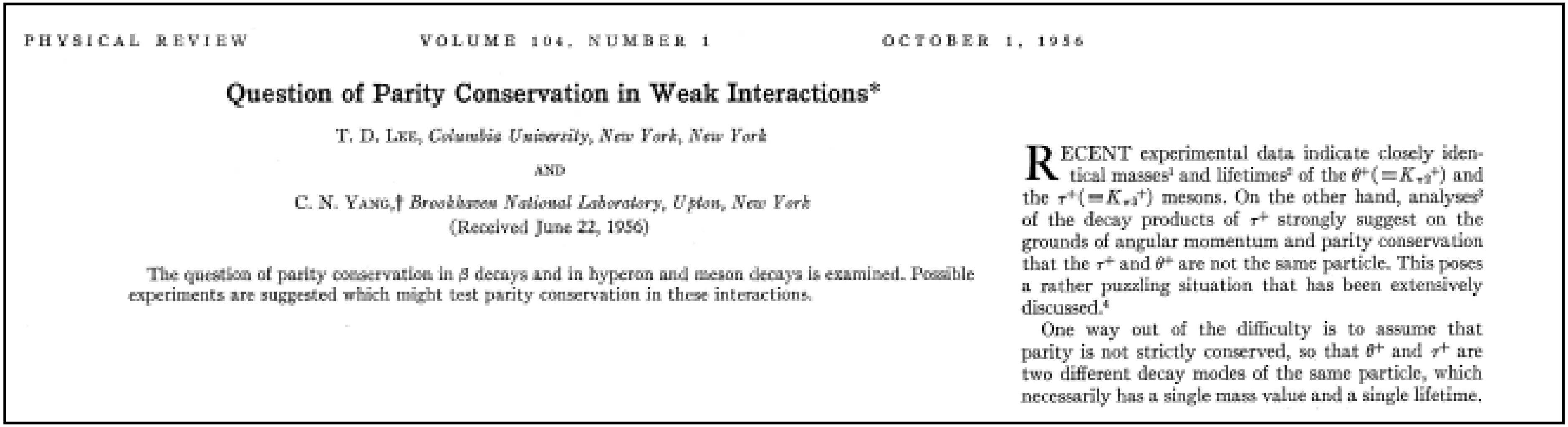
Not clear which of the observed particles are the same particles but diff. decay chains and which are really different particles.

Most famous example: θ / τ puzzle

θ and τ particle known to have the same mass, however as they decayed to final states with different parity they were believed to be different particles:

$$\tau^+ \rightarrow 3\pi \quad \text{Parity } P = -1 \qquad \theta^+ \rightarrow 2\pi \quad P = +1$$

T.D. Lee and C.N. Yang proposed that τ^+ and θ^+ are the same particle and that parity P is violated in weak decays. Shortly after this proposal parity violation was confirmed experimentally by C.S. Wu (1956).



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Question of Parity Conservation in Weak Interactions*

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(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

RECENT experimental data indicate closely identical masses[1] and lifetimes[2] of the $\theta^+(\equiv K_{\pi 2}^+)$ and the $\tau^+(\equiv K_{\pi 3}^+)$ mesons. On the other hand, analyses[3] of the decay products of τ^+ strongly suggest on the grounds of angular momentum and parity conservation that the τ^+ and θ^+ are not the same particle. This poses a rather puzzling situation that has been extensively discussed.[4]

One way out of the difficulty is to assume that parity is not strictly conserved, so that θ^+ and τ^+ are two different decay modes of the same particle, which necessarily has a single mass value and a single lifetime.

With the first proton synchrotrons:

- Cosmotron at BNL (1951) $\rightarrow$ 3.2 GeV
- Bevatron at BNL (1954) $\rightarrow$ 6.2 GeV

It was possible to produce "strange" particles copiously in strong interaction in association with other strange particles, e.g.:

$$\pi^+ + p \rightarrow K^+ + \overline{K}^0 + p, \quad \text{for } E_\pi > 1.5\,\text{GeV}$$

$$S = 1 \quad -1$$

From the observed large production cross section in strong interaction it was concluded that the lifetime should be only O(10^{-20} s) if the new particles were decaying strongly: strange particles decay weakly.

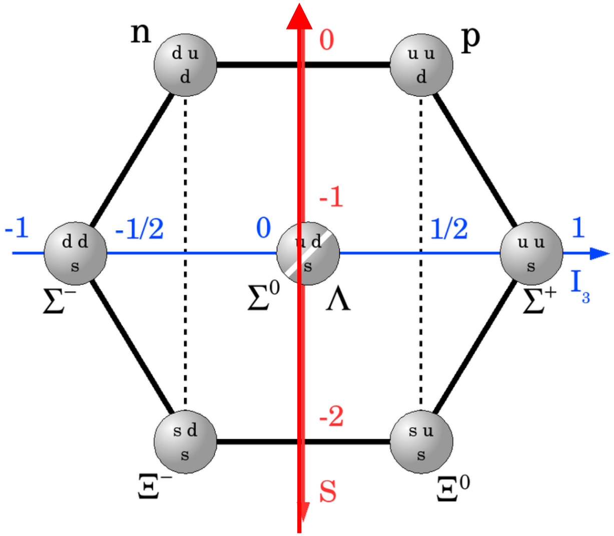
Introduction of a new additive quantum number strangeness which is conserved in strong interaction but which is violated in weak decays.

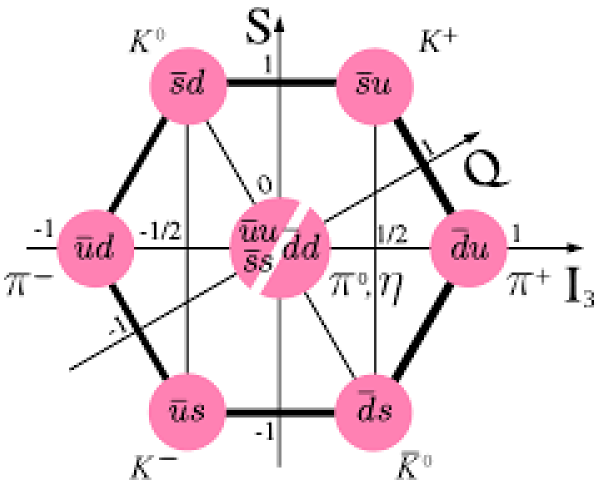
The new quantum number together with the isospin concept opened the way to the flavor SU(3) classification of hadrons and the introduction of the static quark model as the fundamental representation by Gell-Mann and Zweig.

1.3 The 8fold-way (M.Gell-Mann) or “three quarks for Master Mark”

J. Joyce, Finnegans Wake

Using the strong isospin and strangeness Gell-Mann was able to order the known spin ½ and spin 3/2 baryons and the spin 0 and 1 mesons in octets and decuplets:





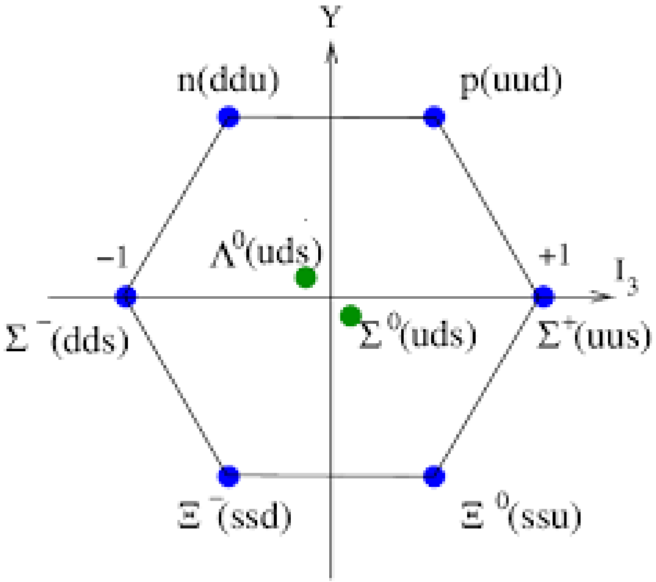
Gell-Mann discovered that the underlying symmetry is a SU(3) group*). Analyzing the spin 3/2 baryon decuplet he predicted in 1962 a missing particle (Ω^-) which was discovered in 1964 (triumph of symmetry ansatz).

*) SU(3) quark flavor symmetry is not exact

Static quark model (Gell-Mann & Zweig, 1964):

The regularities of the hadron multiplets can be accounted for by introducing 3 types of fermion constituents of the hadrons = quarks: u, d, s

Q-flavor	B	I	I_3	S	Q/e = ½ (B+S) + I_3
u	1/3	½	+ ½	0	+2/3
d	1/3	½	- ½	0	-1/3
s	1/3	0	0	-1	-1(3



The symmetry between of the hadrons is understood as the SU(3) quark-flavor symmetry of the u, d and s-quark (not exact!).

1.4 Prediction of the 4th quark

By analyzing “weak decays” of hadrons an experimental finding is that $\Delta S = 1$ transitions are suppressed w/r to $\Delta S = 0$ decays by factor of about ×20 (phase space corrected) e.g. $K^+ \to \mu^+ \nu_\mu$ and $\pi^+ \to \mu^+ \nu_\mu$

The smaller decay rates of $\Delta S = 1$ transitions is accounted for by the Cabibbo theory: In this model the d and the s-quark participating in the weak interaction are rotated w/r to the original flavor states by an angle θ_C:

$$\begin{pmatrix} |u\rangle \\ |d'\rangle \end{pmatrix} = \begin{pmatrix} |u\rangle \\ \cos\theta_c |d\rangle + \sin\theta_c |s\rangle \end{pmatrix}$$

$\theta_C \approx 13^o, \sin\theta_C \approx 0.05$

explains the suppression

Subsequently, an experimentally very puzzling and not understood result of kaon physics was the very tiny branching fraction of the decay $K_L^0 \to \mu^+ \mu^-$

$$\mathcal{B}\left(K_L^0 \to \mu^+ \mu^-\right) \simeq \left(6.84 \pm 0.11\right) \cdot 10^{-9}$$

The 3-quark model would predict a significantly larger branching ratio:

$$\mathcal{M}_u = g^2 \cos\theta_c \sin\theta_c$$

In modern language: in the 3-quark model the GIM-suppression is deactivated.

Glashow, Iliopoulos, Maiani (1970) (Phys. Rev D2 (1970) 1285)

Introduction of a new heavy up-type quark to complete a new 2nd quark doublet fulfilling flavor symmetry:

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \qquad \text{with} \qquad \begin{pmatrix} |d'\rangle \\ |s'\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} |d\rangle \\ |s\rangle \end{pmatrix}$$

With the new c-quark there exists a 2nd amplitude to $K_L^0 \to \mu^+\mu^-$

$$\mathcal{M}_c = -g^2 \cos\theta_c \sin\theta_c$$

$\mathcal{M}_c$ carries a minus sign (unitarity of the 2×2 mixing matrix) relative to $\mathcal{M}_u$

In the limit of perfect flavor symmetry (massless quarks) the two amplitudes cancel each other and the branching ratio $K_L^0 \to \mu^+\mu^-$ is exactly zero (true only for 2 generation model, for 3 generations there is also the top quark).

Remark: In the same paper GIM also analyzed the neutral kaon mixing (another flavor changing neutral current transition):

Mixing frequency
$$\Delta m_K \sim G_F\left(-\cos^2\theta_C \sin^2\theta_C\, f\left(m_u\right)+\cos^2\theta_C \sin^2\theta_C\, f\left(m_c\right)\right)$$
$$\approx G_F m_c^2 \cos^2\theta_C \sin^2\theta_C \qquad \text{for } m_c \gg m_u$$

From the measurement of the mixing frequency the authors concluded that m_c must not be larger than 3…4 GeV.
Following similar arguments Gaillard & Lee predicted $m_c \approx$ 1.5 … 2 GeV.
Although this is an impressive prediction the evaluation suffered under some short-cuts.

However, it is interesting to note that the story repeated for the prediction of the top-quark mass: from the observation of the B^0 B^0 mixing one was able to conclude the m_t > 36 GeV (there the reasoning was correct).

1.5 Discovery of the charm quark

November Revolution in 1974

S.C.C. Ting et al. at BNL: $p(28\,\mathrm{GeV}) + Be \rightarrow \boxed{e^+e^-}X$

B. Richter et al. at SLAC: $@3.1\,\mathrm{GeV} : e^+e^- \rightarrow \boxed{e^+e^-}$

New sharp, heavy &
very narrow
resonance

Interpretation: $c\bar{c}$ resonance w/ quantum numbers of the vacuum.

Reason for very narrow width:

Decay kinematically forbidden

$m(c\bar{c}) < m(D\bar{D})$

OZI suppressed → narrow resonance

3-gluon exchange:
1-gluon not possible because of colour
2-gluons not possible because of C= –1

- Both experiments were very different but discovered the same particle
- SLAC experiment (Mark-I) also found excited cc-states: $\psi(2s), \psi(3s)$

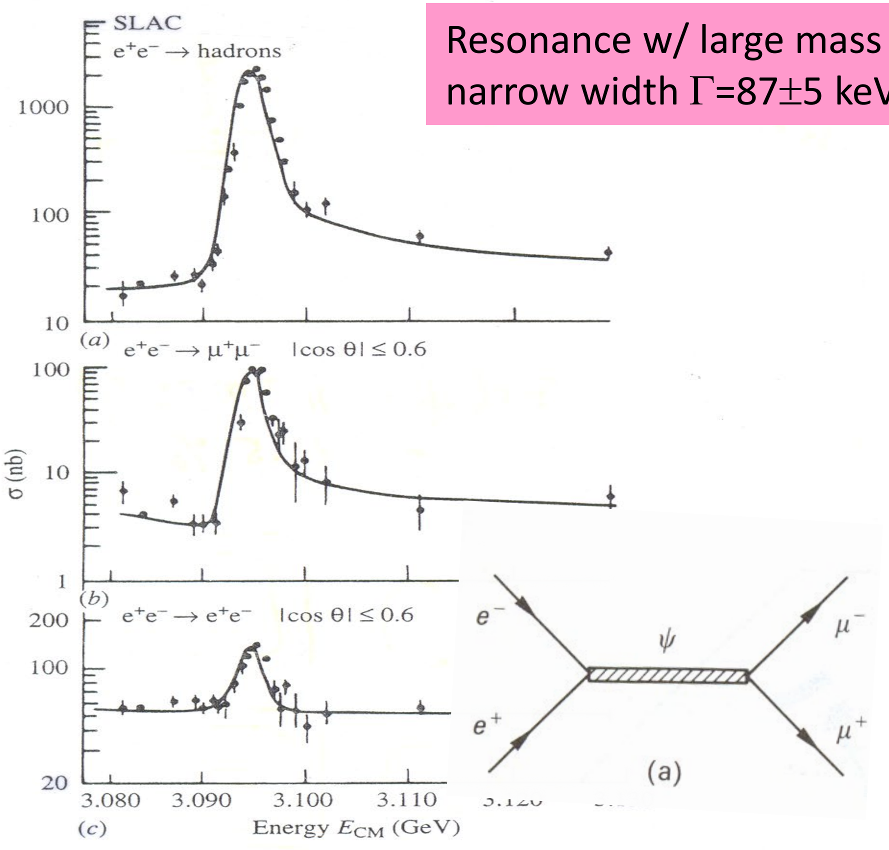
Particle is today called J/ψ

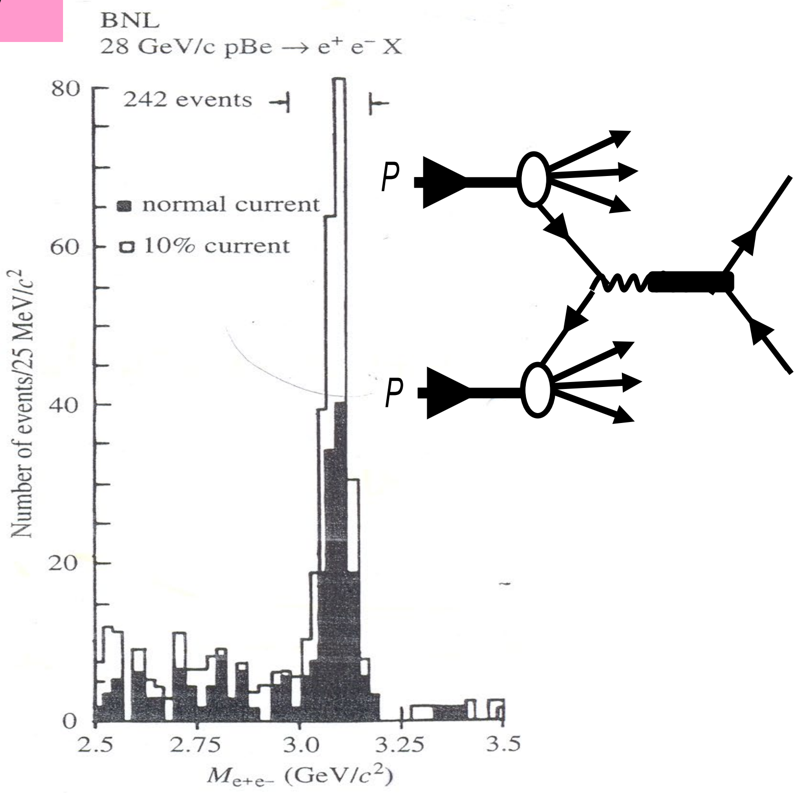
1974: "November Revolution" – Discovery of the J/ψ, bound state of new quark

SLAC $e^+e^- \rightarrow \text{hadrons}, e^+e^-, \mu^+\mu^-$

BNL p(28 GeV)+Be $\rightarrow e^+e^-X$

Resonance w/ large mass narrow width Γ=87±5 keV





Not original paper

1.6 Discovery of the b (beauty, bottom) quark

Analyzing the general structure of the quark mixing matrix Kobayashi & Maskawa (1973) concluded that in order to explain CP violation in hadron decays (discovered in 1964 in the neutral kaon system) one needs a minimum of 3 quark generations. → Nobel prize in physics in 2008

b-quark discovery: Υ-resonance at 9.46 GeV

L.M. Ledermann et al.,
Fermilab, 1977
PRL 39 (1977) 252.

$$p\left(400\,\text{GeV}\right) + Cu \rightarrow \underbrace{\mu^+\mu^-}_{\Upsilon-\text{resonance}} + X$$

(very heavy new narrow resonance)

1.7 Discovery of the top quark

Constraints from indirect measurements:

- m_t > 35 GeV from $B^0\overline{B}^0$ oscillation
- $m_t \approx$ 175 GeV from precision electroweak measurements

Radiative corrections modify the tree level relation between M_W and $\sin^2\theta_W$

Tree-level:

$$\sin^2\theta_w = 1 - \frac{M_W^2}{M_Z^2}$$

Loop-level:

$$\sin^2\theta_{w,eff} = (1+\Delta R)\cdot\sin^2\theta_w$$

The only machine in the 1990s with sufficient energy to discover the top quark was TEVATRON: $p\bar{p}$ at 2 TeV

How to discover the t-quark?
There is no tt-resonance: t-quark
decays faster than hadronization time

Lifetime of the t-quark: $\Gamma_{top} = \frac{G_F^2 m_t^3}{8\pi\sqrt{2}}\left(1 - \frac{M_W^2}{m_t^2}\right)\left(1 + 2\frac{M_W^2}{m_t^2}\right)\left[1 + f\left(\alpha_s\right)\right]$

$$\Gamma_{top} \approx 1.3\,\text{GeV} \Rightarrow \tau_{top} \approx 0.5 \cdot 10^{-24}\,\text{s}$$

Hadronization time: $\tau_{had} \sim \frac{0.5\,\text{fm}}{c} \approx 0.2 \cdot 10^{-23}\,\text{s}$

→ Need to reconstruct the top-quark from decay topology:

$$m_t = m_{inv}\left(b\text{-jet}, W \to \text{jet}_1\text{jet}_2\right)$$

Discovery at TEVATRON (1995)

Top-Quark discovery

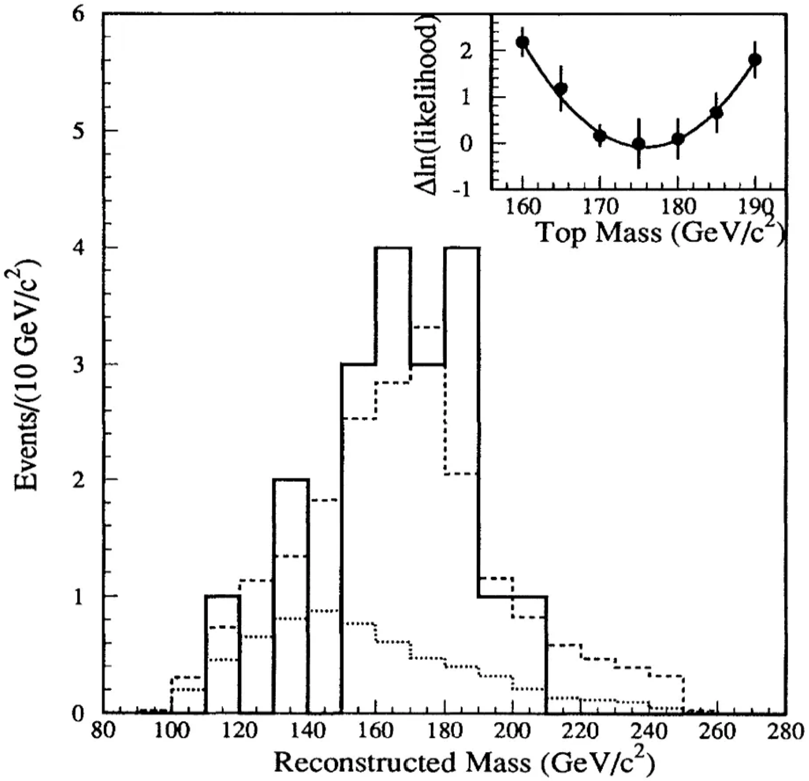


FIG. 3. Reconstructed mass distribution for the b-tagged $W+ \geq 4$-jet events (solid). Also shown are the background shape (dotted) and the sum of background plus $t\bar{t}$ Monte Carlo simulations for $M_{\text{top}} = 175\ \text{GeV}/c^2$ (dashed), with the background constrained to the calculated value, $6.9^{+2.5}_{-1.9}$ events. The inset shows the likelihood fit used to determine the top mass.

Observation of Top Quark Production in pp Collisions with the Collider Detector at Fermilab

F. Abe *et al.* (CDF Collaboration)
Phys. Rev. Lett. 74, 2626.

M_{top} = 176 ±8(stat) ±10(syst) GeV/c2

1.8 Limits on a possible "sequential fourth" generation

1) From e^+e^- cross sections one knows the number of active quark flavors:

$$R_{had} = \frac{\sigma(ee \to \text{hadrons})}{\sigma(ee \to \mu\mu)} = N_C \cdot \sum_{q_f} e_{q_f}^2$$

Puts limits up to $\frac{1}{2}\sqrt{s_{\max}} \approx 100\,\text{GeV}$

2) Constraints on heavy fourth generation from Higgs production

Presence of additional heavy quarks will increase the effective ggH coupling by a large factor, i.e. we would expect an enhanced Higgs production rate at the LHC w/r to the Standard Model rate.

Observed Higgs rate excludes the existence of a heavy 4th generation.

Triangle Anomalies (Adler-Belle): Equal number of letpon & quark generations

There are one-loop diagrams that violate
the local gauge symmetry of the theory.

E.g.: Anomaly with SU(2)$_L$ and U(1)$_Y$ fields.

Cancellation of anomalies necessary to ensure the consistency of the theory:
→ Constraints on the fermion content of the Standard Model.

To vanish the charges in a fermion generation need to add-up to zero:

$$\sum_{doublets} Q = 0 \qquad \text{For each generation:} \quad -1 + 3 \cdot \frac{2-1}{3} = 0$$

Only possible if there are equal number of fermion and quark generations.