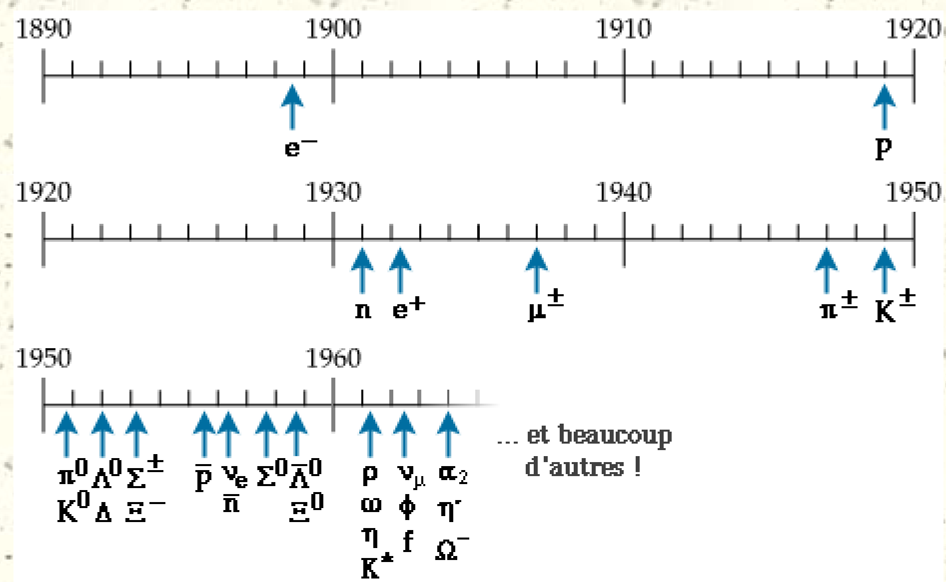
L'ère des quarks

1964 - 1973

1964 - Bilan

- Fantastique succès de la QED* (Feynman)
- Doutes sur :
  - L'interaction faible (Fermi)
  - L'interaction forte (Yukawa)
- Une foultitude de particules élémentaires !



2 familles de leptons

(e,ν_e) (μ,ν_μ)

+ Plein de hadrons

* Électrodynamique quantique, voir « l'ère du Z° »

Résumons-nous…

- Particules
  - Les hadrons (sensibles à l'interaction forte)
    - Mésons (B=0)
    - Baryons (B=+1)
  - Les leptons (B=0, insensibles à l'int. forte)
- Lois de conservation
  - Charge électrique
  - Nombre baryonique
  - Étrangeté, sauf interaction faible !
  - …

§ 1.1.4
§ 1.1.5

Particules au début des années 60…

Tab. 1.1

m(MeV)	-1	0	+1	+2	S
Des baryons (B=+1)					
1530	Ξ^{*-}	Ξ^{*0}			-2
1385	Σ^{*-}	Σ^{*0}	Σ^{*+}		-1
1300	Ξ^{-}	Ξ^{0}			-2
1232	Δ^{-}	Δ^{0}	Δ^{+}	Δ^{++}	0
1190	Σ^{-}	Σ^{0}	Σ^{+}		-1
1115		Λ^{0}			-1
940		n	p		0
Des mésons (B=0)					
547		η			0
495	K^{-}	$\bar{K}^{0}$			-1
495		K^{0}	K^{+}		+1
140	π^{-}	π^{0}	π^{+}		0
Des leptons (B=0)					
106	μ^{-}		μ^{+}		0
0,511	e^{-}		e^{+}		0
0		ν			0

Deux remarques :

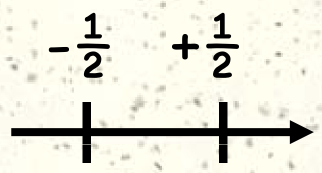
1/ On connaît aussi quelques antibaryons (B = -1) non portés au tableau :
- Même masse,
- Charge opposée,
- Étrangeté opposée.

2/ Sur même ligne, les particules n'ont pas rigoureusement la même masse (qqs MeV de différence, sauf si elles sont antiparticules)

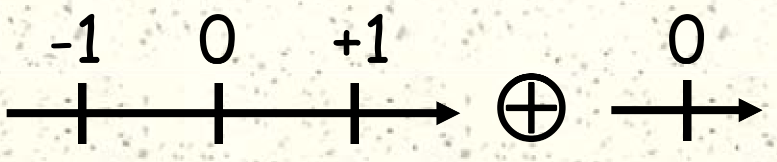
Apparente anarchie…

Un soupçon de théorie des groupes

- Symétries <-> nombres quantiques
  - La théorie des groupes permet de construire à partir de symétries, des objets les respectant, de les composer et de caractériser les quantités conservées.
  - Ex : groupe des rotations <-> moment cinétique
- SU(2) (matrice spéciale unitaire 2D)
  - 1 nombre quantique prenant des valeurs demi-entières : le spin

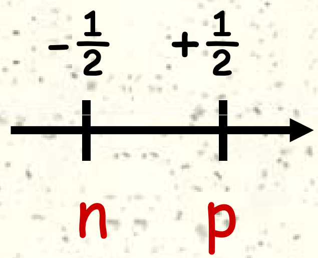


  - Un doublet élémentaire
  - Composition des spins :
    - $2 \otimes 2 = 3 \oplus 1$



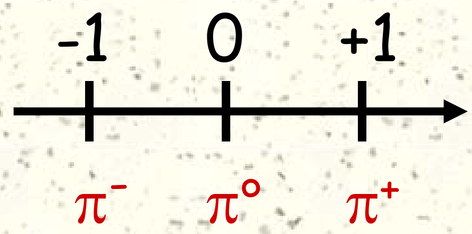
Le spin isotopique…

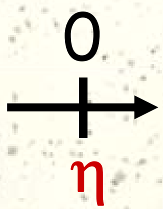
- 1931 Heisenberg a l'idée d'un « isospin »
  - (ou spin isotopique)
  - Proton & neutron (1931) sont « symétriques » pour l'interaction forte.
  - Ils se composent dans les noyaux…



- 1935 Yukawa invente les pions
  - $p^+ \rightarrow \pi^+ + n$
  - $p^+ \rightarrow \pi^\circ + p^+$
  - $n \rightarrow \pi^- + p^+$

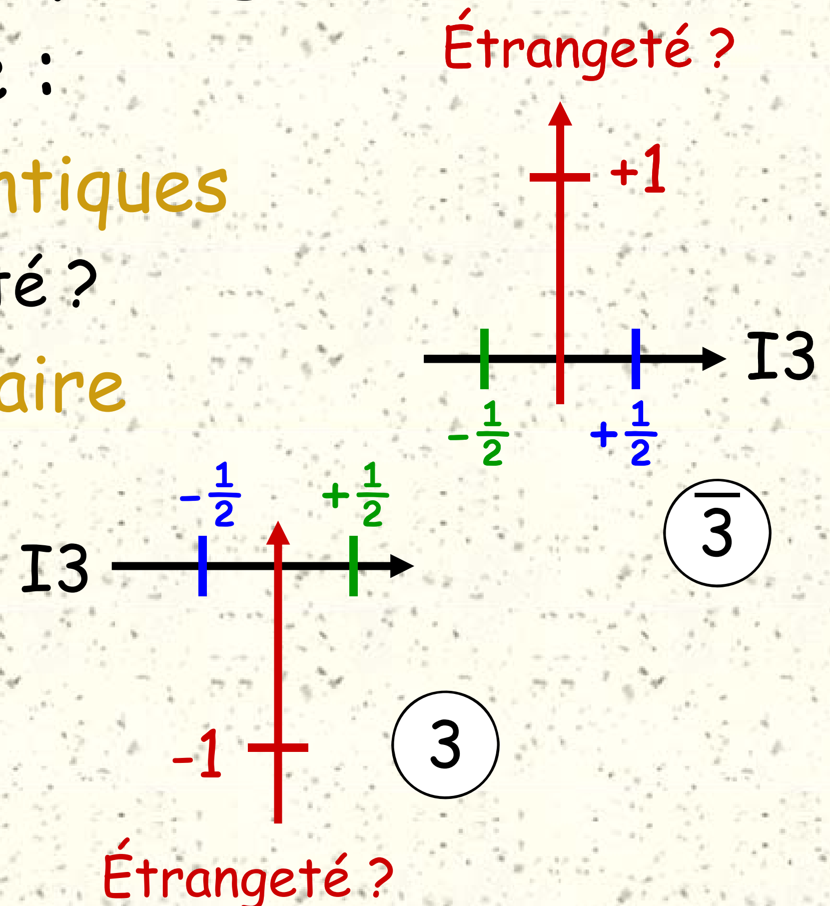
$$(n,p) \otimes (\bar{p},\bar{n}) = (\pi^- \pi^\circ \pi^+) \oplus (\eta)$$





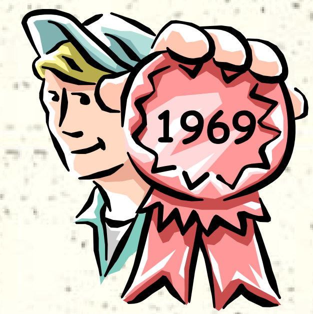
Groupe SU(3)

- Pour ranger les particules étranges, essayons un groupe plus grand !
- SU(3) par exemple :
  - Deux nombres quantiques
    - Isospin et étrangeté ?
  - Un triplet élémentaire
  - Anti-triplet

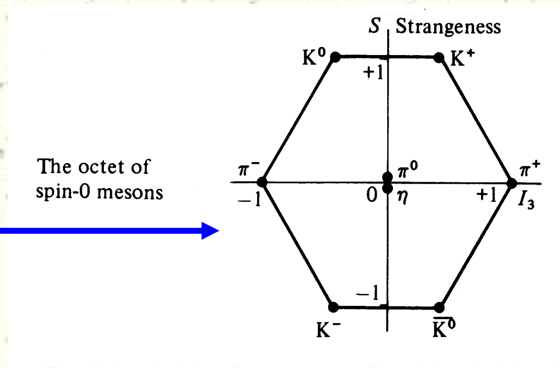


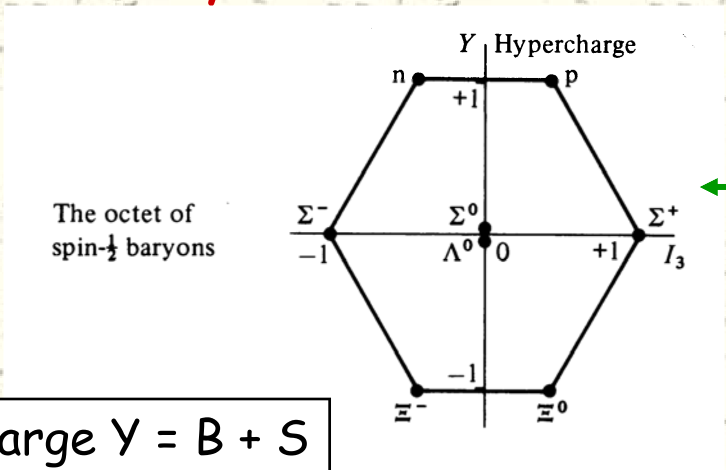
Reste à essayer de les composer et à ranger nos particules

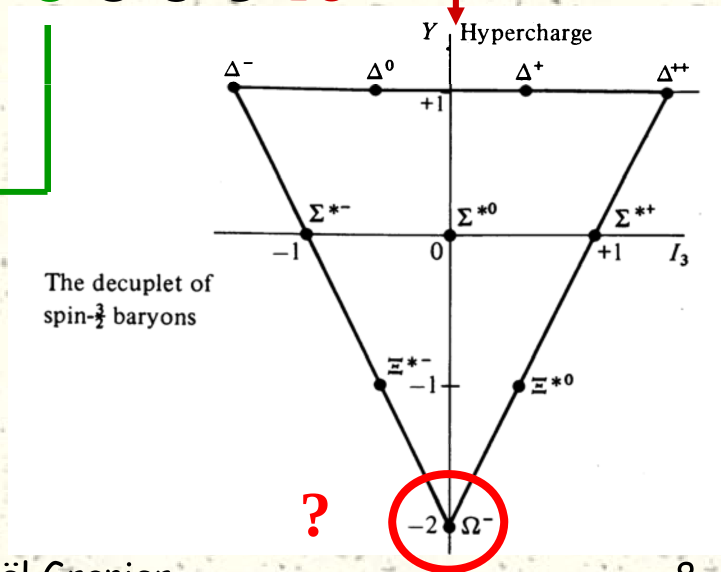
Un peu d'ordre…



- **1961** : Murray Gell-Mann comprend qu'on peut ranger les hadrons en multiplets de SU(3)
  - Les mésons : $3 \otimes \bar{3} = 1 \oplus 8$
  - Les baryons : $3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus 8 \oplus 10$



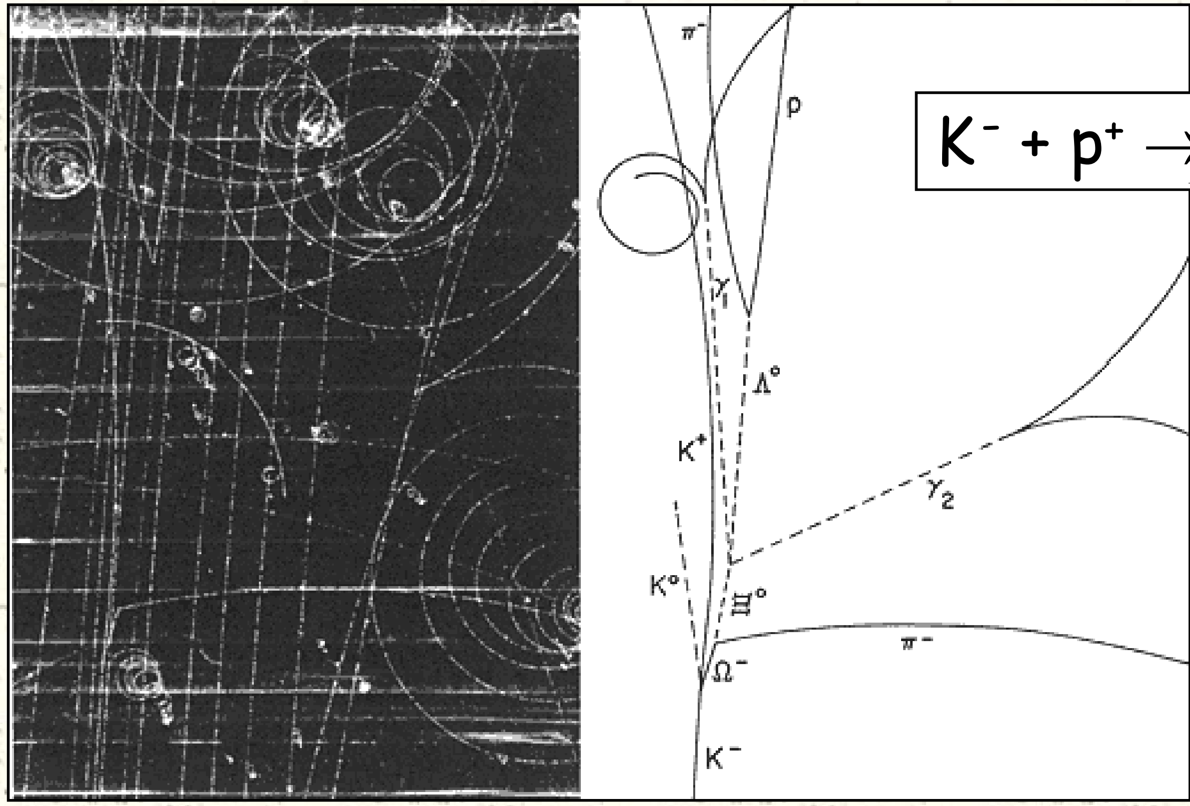




Hypercharge $Y = B + S$
Isospin $= Q - Y/2$

Prédiction de SU(3) : le Ω^-

- Gell-Mann prédit le Ω^-, d'étrangeté –3, de masse ~1680 MeV (saut de ~ 150 MeV par unité d'étrangeté)
- Produit en 1964 par Barnes et al. à Brookhaven



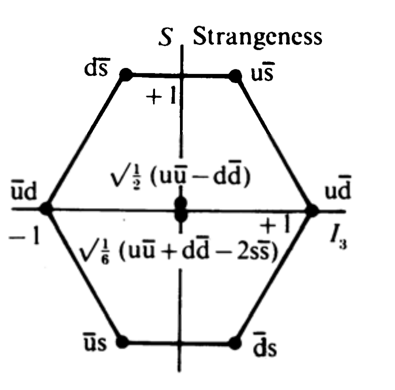
$$K^- + p^+ \rightarrow \Omega^- K^+ K^\circ$$

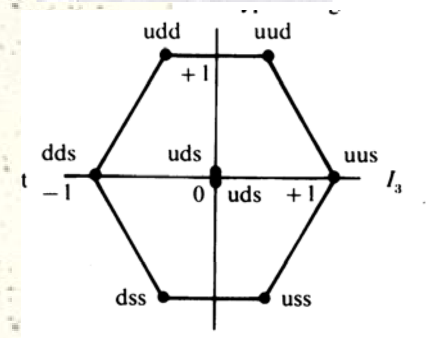
En terme de quarks

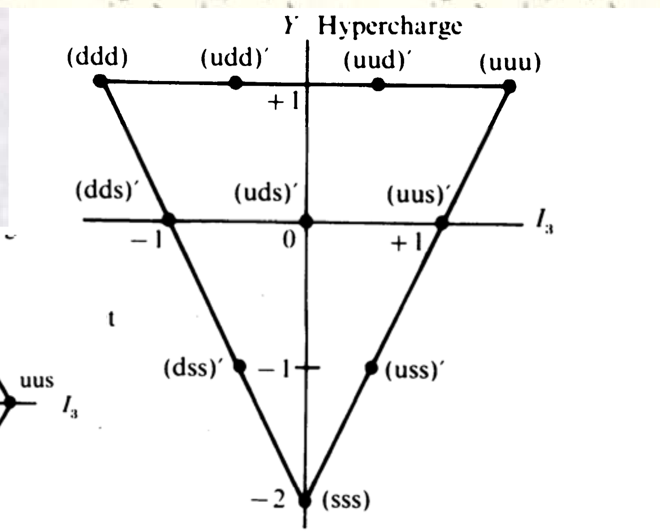
§ 1.2.1

- 1964 : Gell-Mann / Zweig ont l'idée de quarks / aces

Particules de spin ½		Charge	Etrangeté
Doublet isotopique	(d,u)	$^{-1}/_3$ $^{+2}/_3$	0
Singulet isotopique	s	$^{-1}/_3$	-1







Mésons = $q\bar{q}$
Baryons = qqq

« Three quarks for Muster Mark » *Finnegan's Wake*, James Joyce (1939)

Formidable ! les hadrons semblent constitués par trois briques élémentaires !

Deux problèmes :

1. Pourquoi $q\bar{q}$ et qqq ? Et pas qq ou $qq\bar{q}$ ou $qqqq$?
2. Ou q ? Pourquoi n'a-t-on jamais vu de quarks ?

La réponse viendra en 1973

Prédiction d'un quatrième quark

- 1964 : quelques papiers suggèrent l'existence d'un quatrième quark…

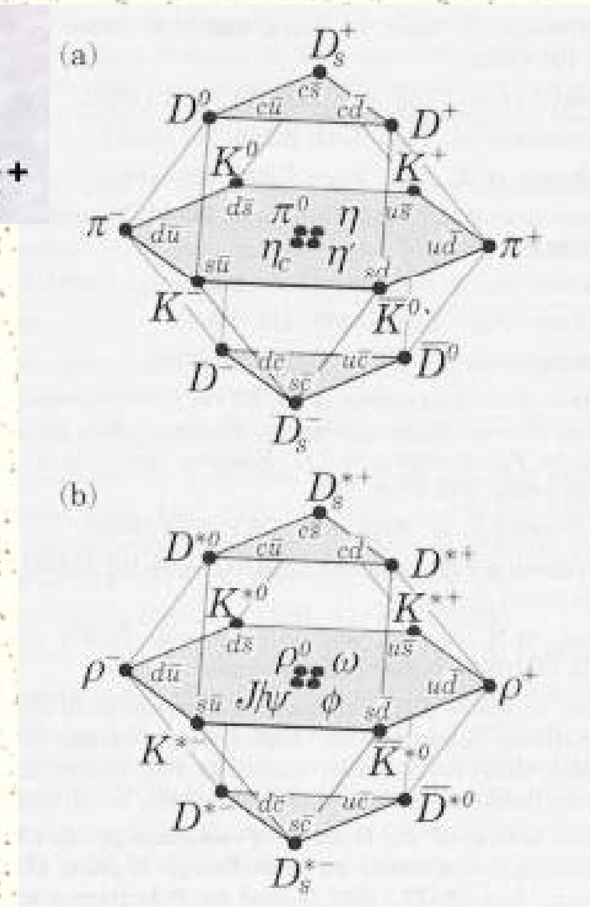
Lepton	Neutrino
Électron	ν_e
Muon	ν_μ

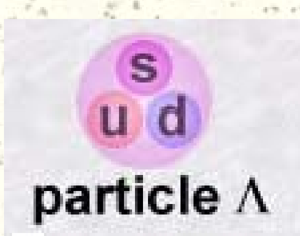
Quark $^{+2}/_3$	Quark $^{-1}/_3$
Up	Down
???	Strange

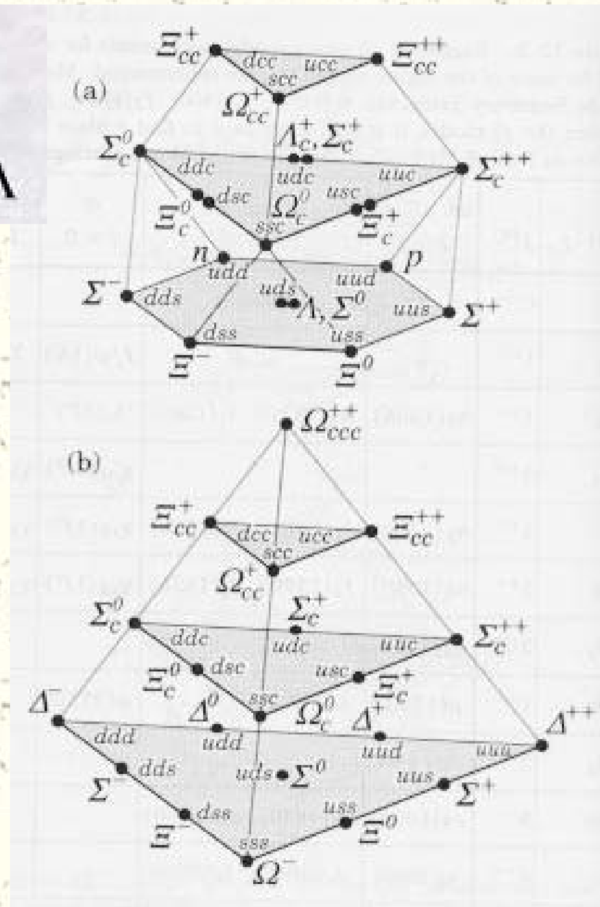
- Glashow, Bjorken « it appears like a charm »
- 1970 : Mécanisme de (GIM) Glashow Iliopoulos Maiani
  - Besoin théorique fort de cette quatrième saveur

Multiplets de SU(4) ?

- Nouvelle zoologie de particules !



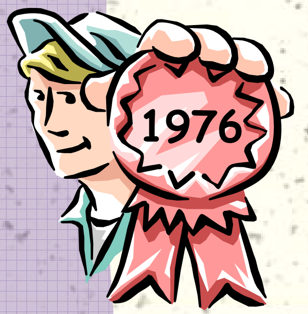


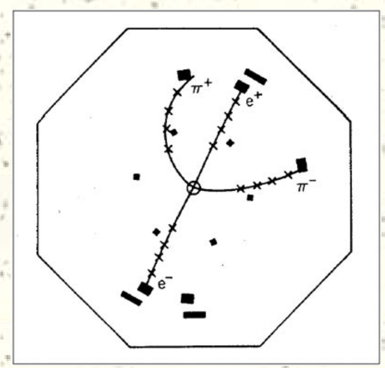


1974 : découverte du J/Ψ

§ 1.2.3

- Indépendamment, Burton Richter et Samuel Ting découvrent une nouvelle particule





Résonance	Le « Ψ »	Le « J »
m = 3,105 GeV	À Stanford	À Brookhaven
Γ < 1,3 MeV	Collisions e+ e-	Proton sur cible

→ première particule charmée : un méson $c\bar{c}$

Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \mathrm{Be} \to e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

This experiment is part of a large program to study the behavior of timelike photons in $p + p \to e^+ + e^- + x$ reactions[1] and to search for new particles which decay into e^+e^- and $\mu^+\mu^-$ pairs.

We use a slow extracted beam from the Brookhaven National Laboratory's alternating-gradient synchrotron. The beam intensity varies from 10^{10} to 2×10^{12} p/pulse. The beam is guided onto an extended target, normally nine pieces of 70-mil Be, to enable us to reject the pair accidentals by requiring the two tracks to come from the same origin. The beam intensity is monitored with a secondary emission counter, calibrated daily with a thin Al foil. The beam spot size is 3×6 mm^2, and is monitored with closed-circuit television. Figure 1(a) shows the simplified side view of one arm of the spectrometer. The two arms are placed at 14.6° with respect to the incident beam; bending (by $M1$, $M2$) is done vertically to decouple the angle (θ) and the momentum (p) of the particle.

The Cherenkov counter C_0 is filled with one atmosphere and C_e with 0.8 atmosphere of H_2. The counters C_0 and C_e are decoupled by magnets $M1$ and $M2$. This enables us to reject knock-on electrons from C_0. Extensive and repeated calibra-

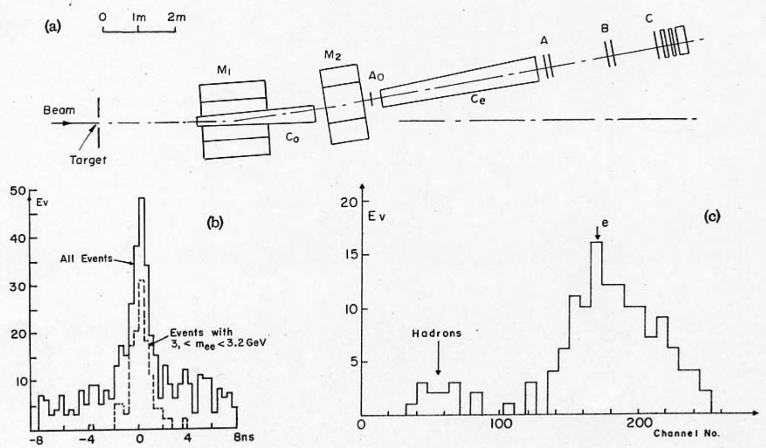


FIG. 1. (a) Simplified side view of one of the spectrometer arms. (b) Time-of-flight spectrum of e^+e^- pairs and of those events with $3.0 < m < 3.2$ GeV. (c) Pulse-height spectrum of e^- (same for e^+) of the e^+e^- pair.

proximately 10^{-34} cm^2.

The most striking feature of J is the possibility that it may be one of the theoretically suggested charmed particles[2] or a's[3] or Z_0's,[4] etc. In order to study the real nature of J,[5] measurements are now underway on the various decay modes, e.g., an $e\pi\nu$ mode would imply that J is weakly interacting in nature.

It is also important to note the absence of an e^+e^- continuum, which contradicts the predictions of parton models.[6]

We wish to thank Dr. R. R. Rau and the alternating-gradient synchrotron staff who have done an outstanding job in setting up and maintaining this experiment. We thank especially Dr. F. Eppling, B. M. Bailey, and the staff of the Laboratory for Nuclear Science for their help and encouragement. We thank also Ms. I. Schulz, Ms. H. Feind, N. Feind, D. Osborne, G. Krey, J. Donahue, and E. D. Weiner for help and assistance. We thank also M. Deutsch, V. F. Weisskopf, T. T. Wu, S. Drell, and S. Glashow for many interesting conversations.

†Accepted without review under policy announced in Editorial of 20 July 1964 [Phys. Rev. Lett. 13, 79 (1964)].

[1]The first work on $p + p \to \mu^+ + \mu^- + x$ was done by L. M. Lederman *et al.*, Phys. Rev. Lett. 25, 1523 (1970).
[2]S. L. Glashow, private communication.
[3]T. D. Lee, Phys. Rev. Lett. 26, 801 (1971).
[4]S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967), and 27, 1688 (1971), and Phys. Rev. D 5, 1412, 1962 (1972).
[5]After completion of this paper, we learned of a similar result from SPEAR. B. Richter and W. Panofsky, private communication; J.-E. Augustin *et al.*, following Letter [Phys. Rev. Lett. 33, 1404 (1974)].
[6]S. D. Drell and T. M. Yan, Phys. Rev. Lett. 25, 316 (1970). An improved version of the theory is not in contradiction with the data.

Discovery of a Narrow Resonance in e^+e^- Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^- \to$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

We have observed a very sharp peak in the cross section for $e^+e^- \to$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ in the Stanford Linear Accelerator Center (SLAC)-Lawrence Berkeley Laboratory magnetic detector[1] at the SLAC electron-positron storage ring SPEAR. The resonance has the parameters

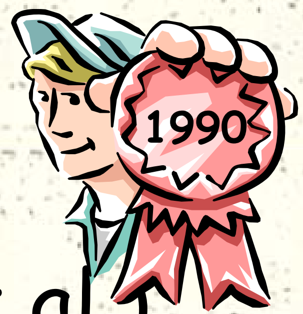
$E = 3.105 \pm 0.003$ GeV,

$\Gamma \leqslant 1.3$ MeV

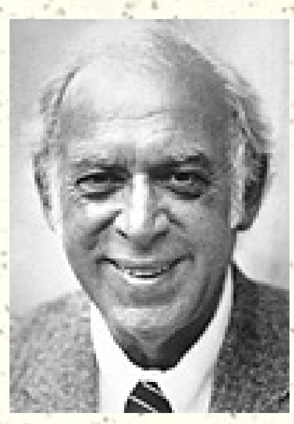
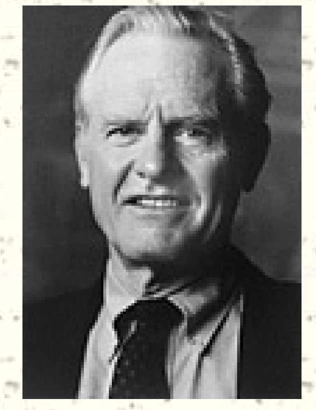
(full width at half-maximum), where the uncertainty in the energy of the resonance reflects the uncertainty in the absolute energy calibration of the storage ring. [We suggest naming this structure $\psi(3105)$.] The cross section for hadron production at the peak of the resonance is $\geqslant 2300$ nb, an enhancement of about 100 times the cross section outside the resonance. The large mass, large cross section, and narrow width of this structure are entirely unexpected.

Our attention was first drawn to the possibility of structure in the $e^+e^- \to$ hadron cross section during a scan of the cross section carried out in 200-MeV steps. A 30% (6 nb) enhancement was

Observation des quarks



- 1969 : Friedman, Kendal, Taylor (et al.) voient une déviation dans la diffusion d'électrons sur des protons explicables par l'existence de « partons » dans le proton…


~ Expérience de Rutherford → noyaux

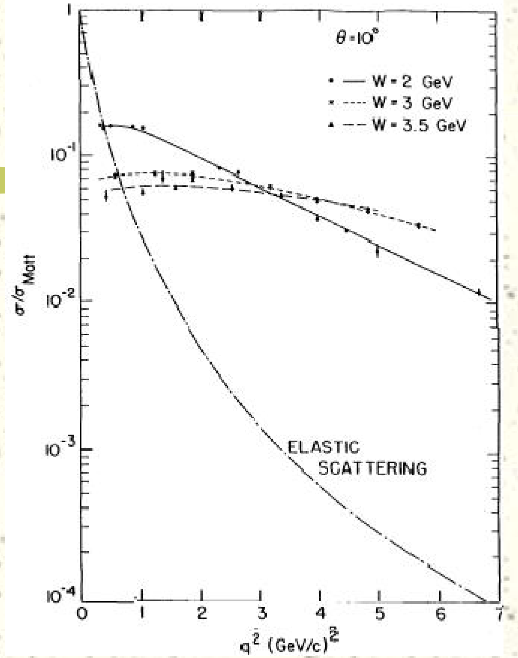
- Les protons ont une « structure » :
  - Des quarks [mais aussi des gluons (1979)]

Observation des quarks

- À Stanford (CA)

Accélérateur linéaire

  - Deux miles (3,2 km)
  - Electrons de 20 GeV



1973 - Bilan

- Fantastiques succès de la QED (Feynman)
- Doutes sur :
  - L'interaction faible (Fermi)
  - L'interaction forte (Yukawa)
- Peu de particules élémentaires !

2 familles de leptons

(e,ν_e) (μ,ν_μ)

2 familles de quarks

(u,d) (c,s)