

L'ère des quarks

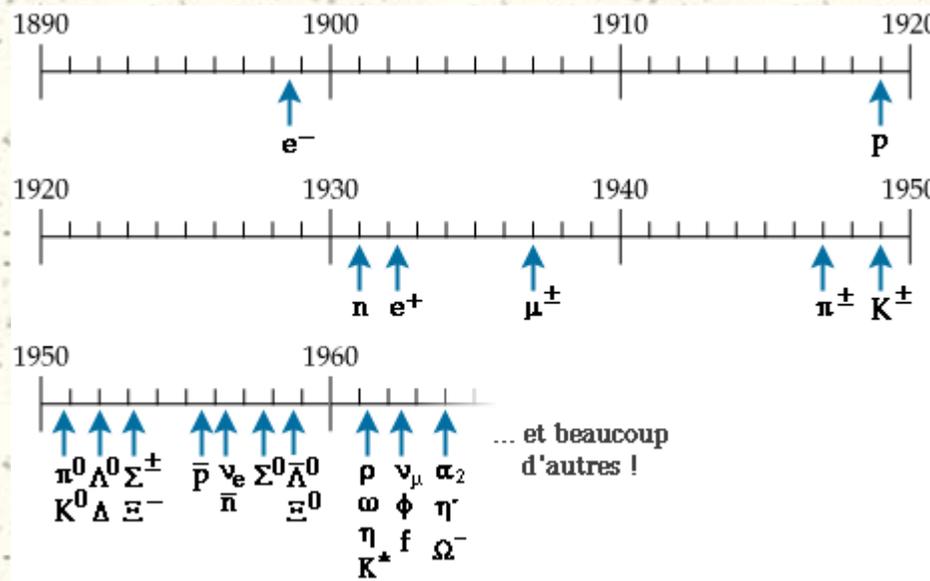


1964 - 1973

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

* Electrodynamique quantique, voir séance sur modèle standard

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 !
- ...

Particules au début des années 60...

| 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^{-} | \overline{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

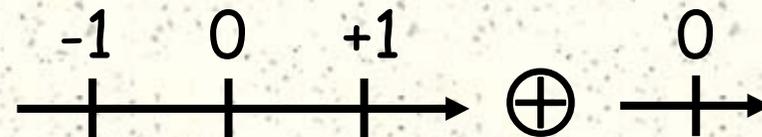
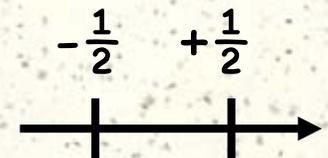
Symétries \leftrightarrow nombres quantiques

- 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 \leftrightarrow moment cinétique

SU(2) (matrice spéciale unitaire 2D)

- 1 nombre quantique prenant des valeurs demi-entières : le spin
- Un doublet élémentaire
- Composition des spins :

- $2 \otimes 2 = 3 \oplus 1$



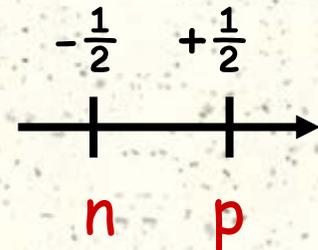
Le spin isotopique...

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...

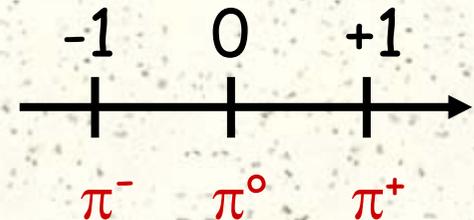


1935 Yukawa invente les pions

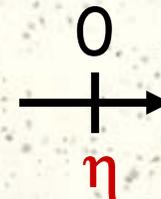
- $p^+ \rightarrow \pi^+ + n$

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

- $n \rightarrow \pi^- + p^+$



$$(n,p) \otimes (\bar{p},\bar{n}) = (\pi^- \pi^0 \pi^+) \oplus (\eta)$$



Groupe SU(3)

Pour ranger les particules étranges, essayons un groupe plus grand !

SU(3) par exemple :

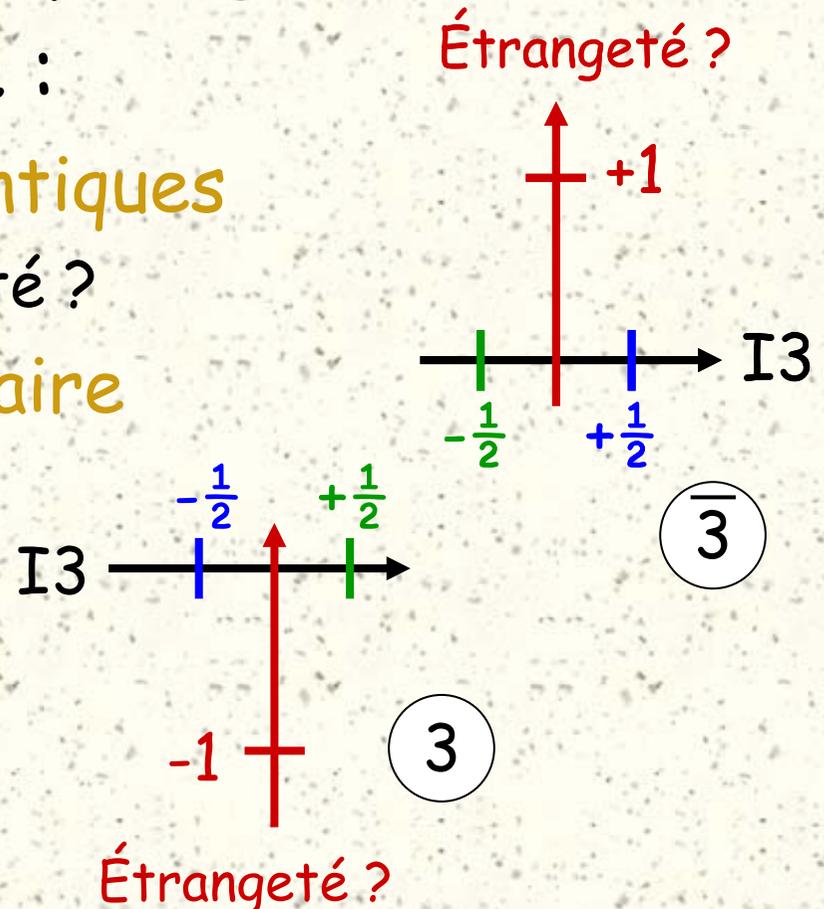
■ Deux nombres quantiques

■ Isospin et étrangeté ?

■ Un triplet élémentaire

■ Anti-triplet

Reste à essayer de les composer et à ranger nos particules



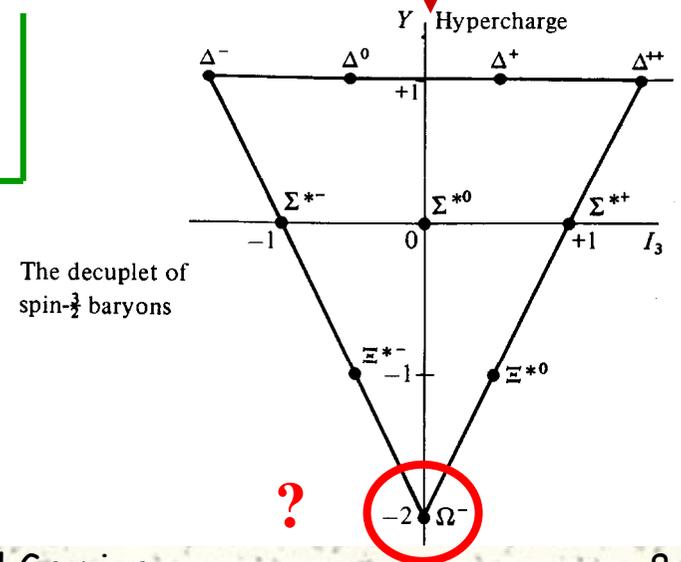
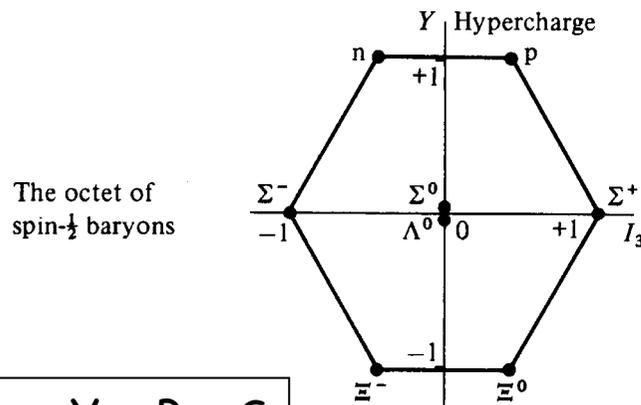
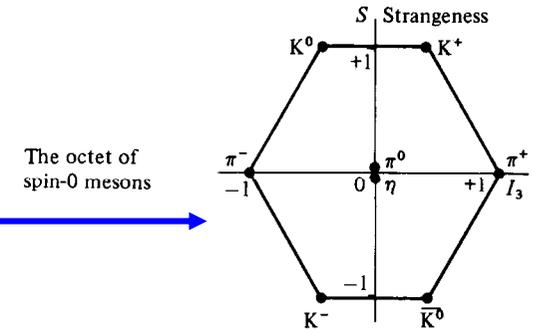
Un peu d'ordre...



1961 : Murray Gell-Mann
comprend qu'on peut ranger
les hadrons en multiplets
de SU(3)

■ Les **mésons** : $3 \otimes \bar{3} = 1 \oplus 8$

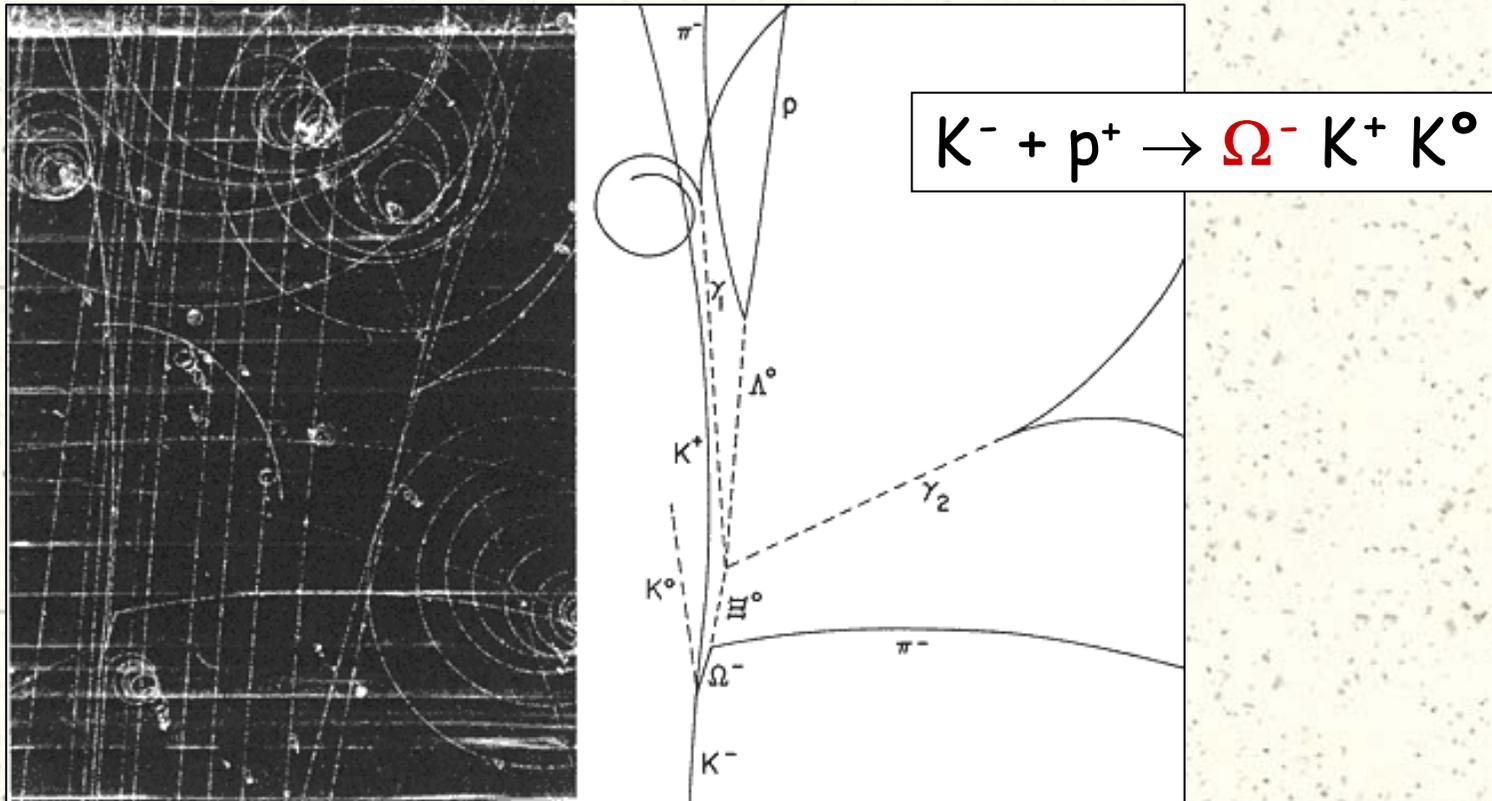
■ Les **baryons** : $3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus 8 \oplus 10$



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

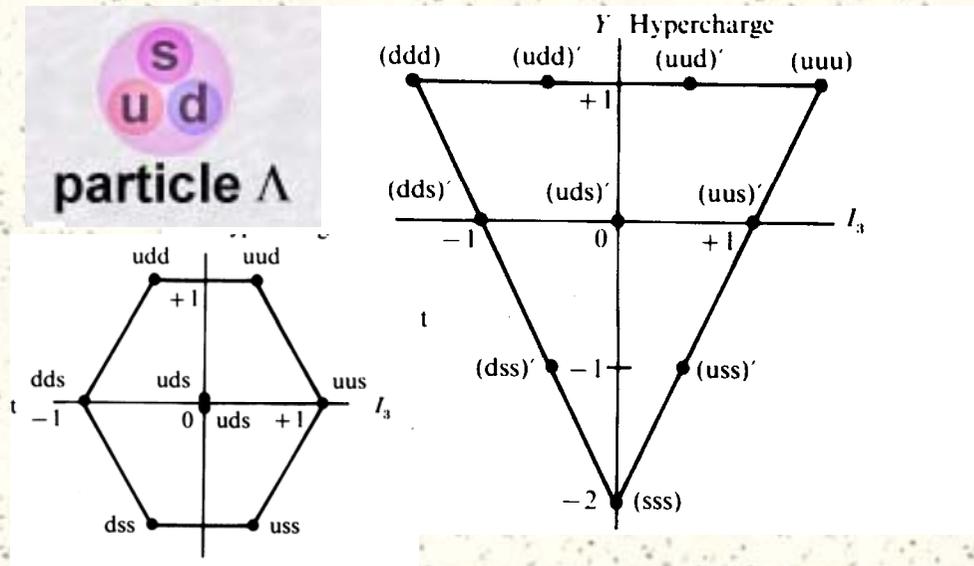
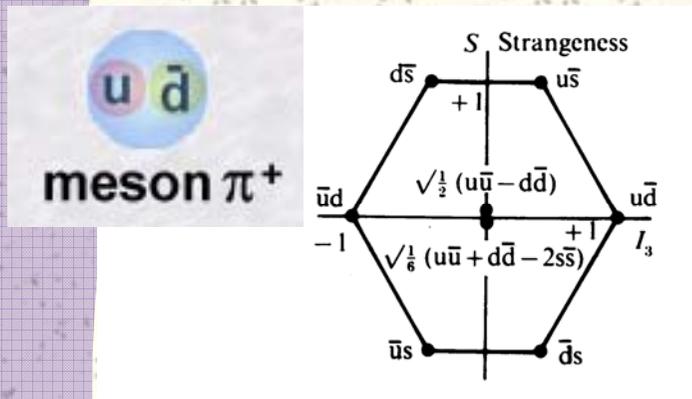


En terme de quarks



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

- Particules de spin $\frac{1}{2}$
- Doublet isotopique (d,u) Charge $-\frac{1}{3}$ $+\frac{2}{3}$ Etrangeté 0
- Singulet isotopique s Charge $-\frac{1}{3}$ Etrangeté -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 | Quark $^{+2/3}$ | Quark $^{-1/3}$ |
|----------|-----------|-----------------|-----------------|
| Électron | ν_e | Up | Down |
| Muon | ν_μ | ??? | Strange |

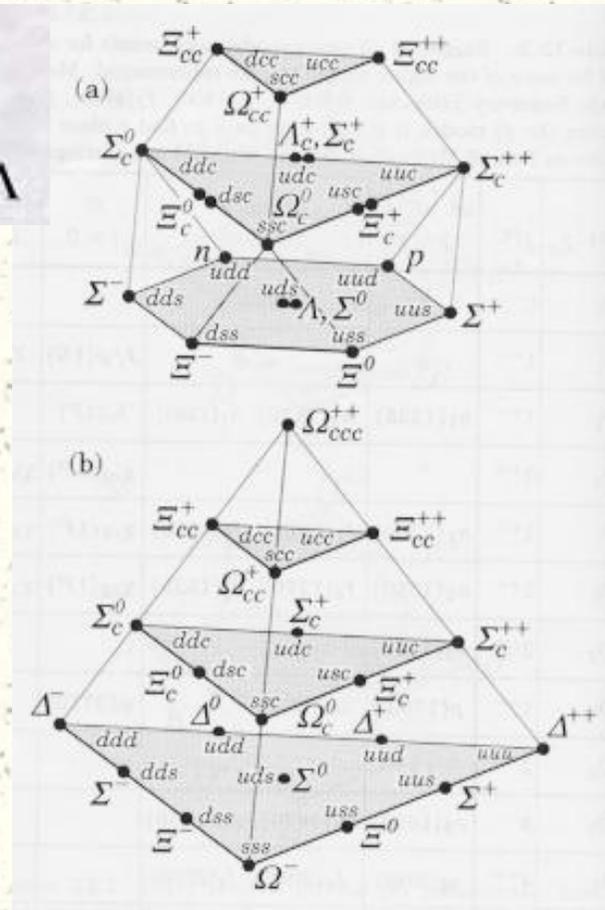
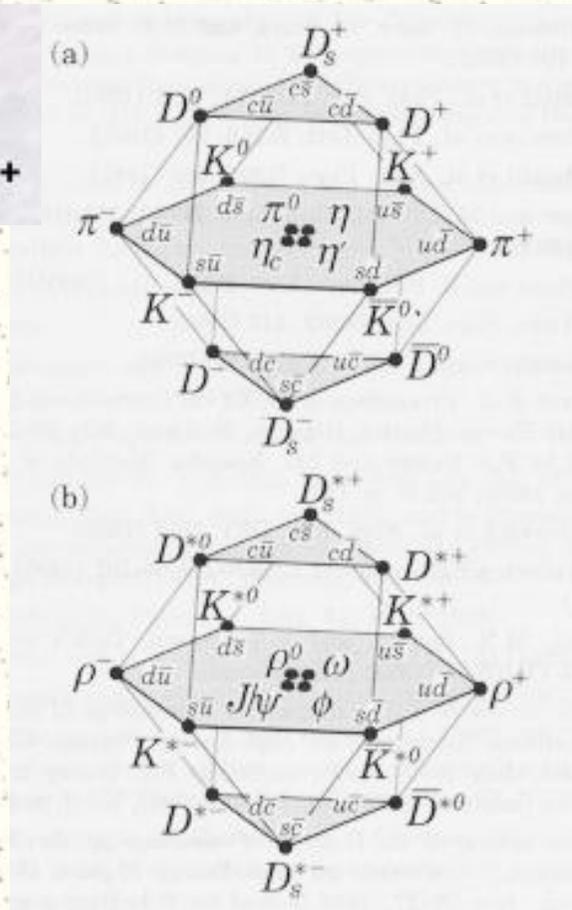
Glashow, Bjorken « it appears like a charm »

1970 Mécanisme de (GIM) Glashow Iliopoulos Maiani

■ Besoin théorique fort de cette quatrième saveur

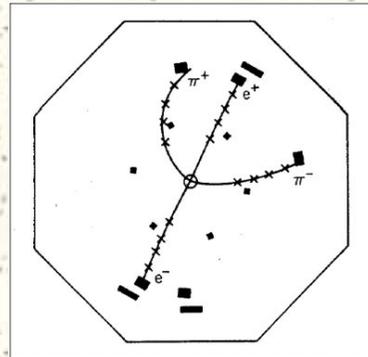
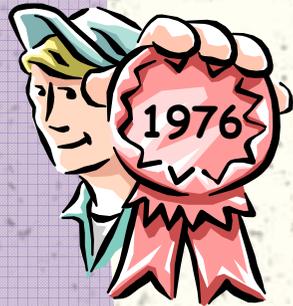
Multiplets de SU(4) ?

Nouvelle zoologie de particules !



1974 : découverte du J/ Ψ

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



Résonance
 $m = 3,105 \text{ GeV}$
 $\Gamma < 1,3 \text{ MeV}$

Le « Ψ »
À Stanford
Collisions $e^+ e^-$

Le « J »
À Brookhaven
Proton sur cible

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

Experimental Observation of a Heavy Particle J^\dagger

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Evershart, P. Goldhagen, J. Leong, T. McCarriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
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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 $p + Be \rightarrow e^+ + e^- + X$ 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 $p + p \rightarrow e^+ + e^- + X$ reactions¹ 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 mm², 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 M_1 , M_2) 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 M_1 and M_2 . This enables us to reject knock-on electrons from C_0 . Extensive and repeated calibra-

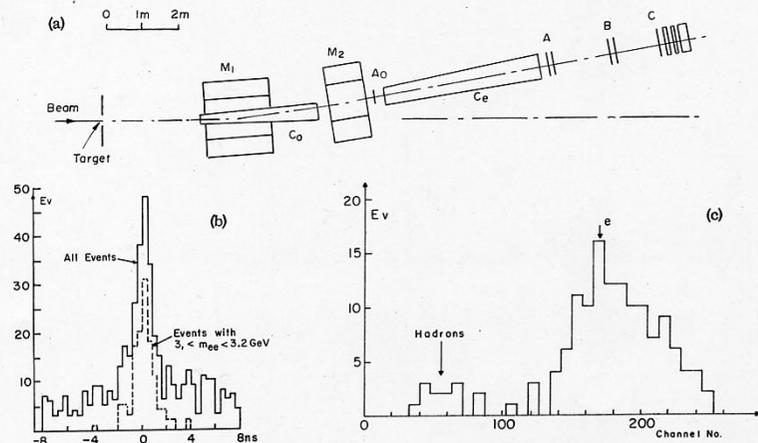


FIG. 1. (a) Simplified side view of one of the spectrometer arms. (b) Time-of-flight spectrum of e^+e^- pairs and of those events with $3.0 < m < 3.2$ GeV. (c) Pulse-height spectrum of e^- (same for e^+) of the e^+e^- pair.

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proximately 10^{-34} cm².

The most striking feature of J is the possibility that it may be one of the theoretically suggested charmed particles² or a 's³ 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 $e\nu$ 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)].

¹The first work on $p + p \rightarrow \mu^+ + \mu^- + X$ was done by L. M. Lederman *et al.*, Phys. Rev. Lett. **25**, 1523 (1970).

²S. L. Glashow, private communication.

³T. D. Lee, Phys. Rev. Lett. **26**, 801 (1971).

⁴S. Weinberg, Phys. Rev. Lett. **19**, 1264 (1967), and **27**, 1688 (1971), and Phys. Rev. D **5**, 1412, 1962 (1972).

⁵After 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)].

⁶S. 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[‡]

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(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^- \rightarrow$ 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 $e^+e^- \rightarrow$ hadrons, e^+e^- , and possibly $\mu^+\mu^-$ in the Stanford Linear Accelerator Center (SLAC)-Lawrence Berkeley Laboratory magnetic detector¹ at the SLAC electron-positron storage ring SPEAR. The resonance has the parameters

$$E = 3.105 \pm 0.003 \text{ GeV,}$$

$$\Gamma \leq 1.3 \text{ MeV}$$

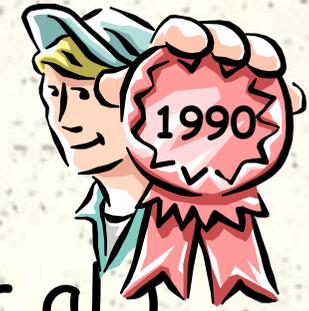
(full width at half-maximum), where the uncertainty in the energy of the resonance reflects the

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 ≥ 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 $e^+e^- \rightarrow$ hadron cross section during a scan of the cross section carried out in 200-MeV steps. A 30% (6 nb) enhancement was

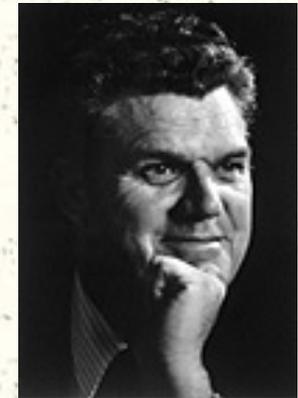
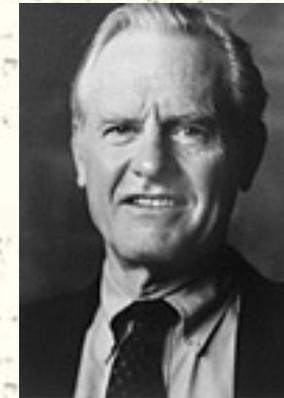
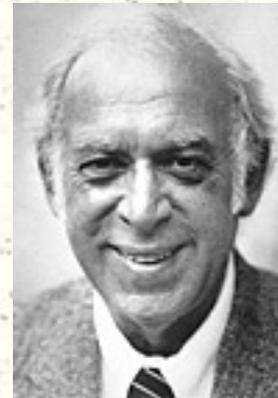
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Observation des quarks



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 » :

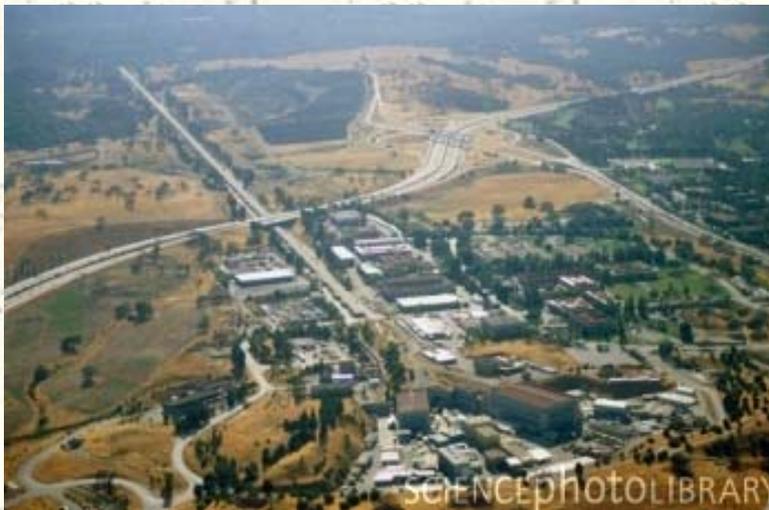
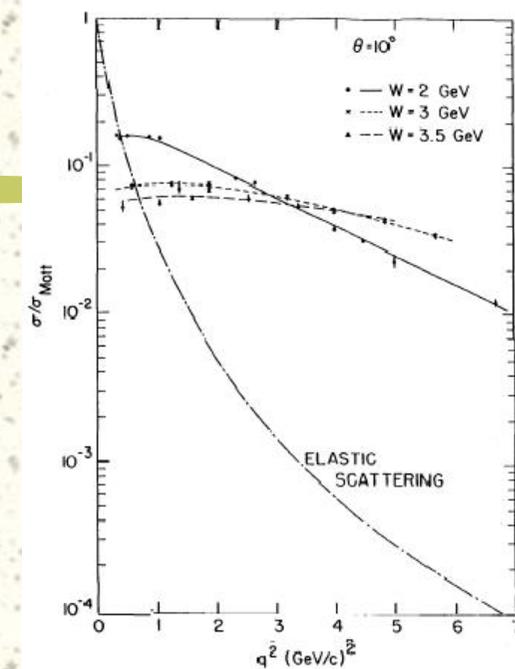
■ Des quarks [mais aussi des gluons (1979)]

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 :
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 - 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)

