

## 5. Einführung in die Teilchenphysik

5.1 Neue Teilchen und Antiteilchen

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# 5.1 Neue Teilchen und Antiteilchen

## 5.1.1 Die ersten Elementarteilchen:

### **1897: Identifizierung des Elektron durch J.J. Thomson**

Das erste Elementarteilchen, elektrisch geladen,  
Ablenkung in elektrischen und magnetischen Feldern  
 $Q = -1e$ ,  $m_e = 511 \text{ keV}/c^2$ , Spin =  $\frac{1}{2} \hbar$ , stabil,  $\tau = \infty$   
Das leichteste elektrisch geladene Teilchen

### **1911 - 1919: Rutherford'sche Streuexperimente, Identifizierung des Wasserstoffkerns als Proton**

### **1930: Neutrino-Hypothese von Pauli**

### **1932: Entdeckung des Neutrons durch J. Chadwick**

**Wechselwirkungen: Gravitation, elektromagnetische Wechselwirkung,  
starke Wechselwirkung (Kernkräfte),  
und schwache Wechselwirkung ( $\beta$ -Zerfall)**

## 5.1.2. Antimaterie

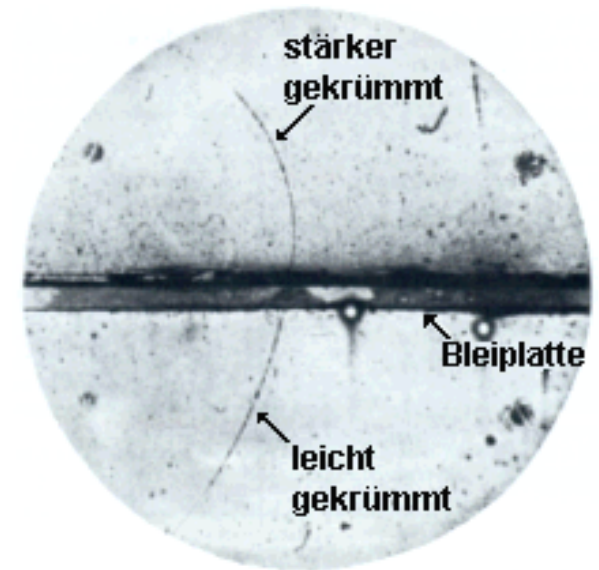
1932: Anderson entdeckt das **Positron**

(systematische Durchmusterung von Nebelkammeraufnahmen von Teilchenspuren, die durch Höhenstrahlung erzeugt wurden, pos. geladen, große Reichweite,  $\neq$  Proton)

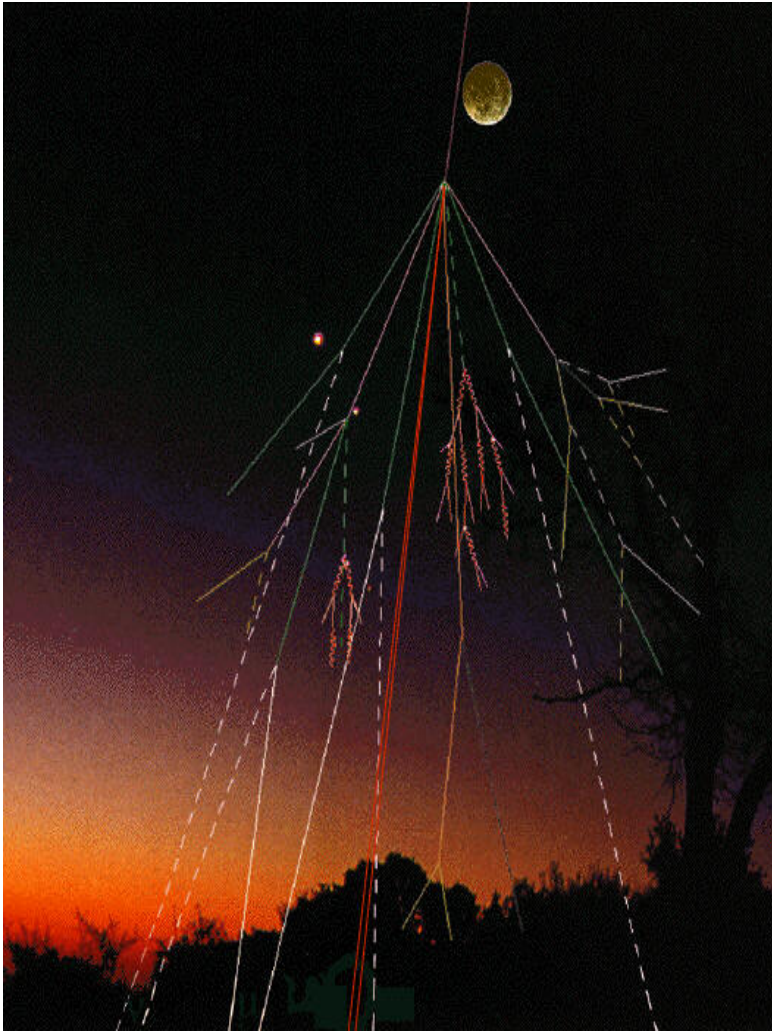
$$Q = +1e, \quad m_e = 511 \text{ keV}/c^2, \quad \text{Spin} = \frac{1}{2} \hbar, \\ \text{stabil (im Vakuum)}, \quad \tau = \infty$$

- Wurde zunächst als positiv geladenes Elektron interpretiert.
- **Feynman / Stückelberg** (Theorie, 40er Jahre)  
Die Lösungen der Dirac-Gleichung, die zu negativen Energien gehören, werden als Zustände positiver Energie von sog. **Antiteilchen** interpretiert.
- **Quantenfeldtheorien** besitzen eine grundlegende Eigenschaft:

zu jedem Teilchen muss es ein Antiteilchen geben, das dieselbe Masse hat, aber entgegengesetzte additive Quantenzahlen  
(Symmetrie zwischen Materie und Antimaterie)

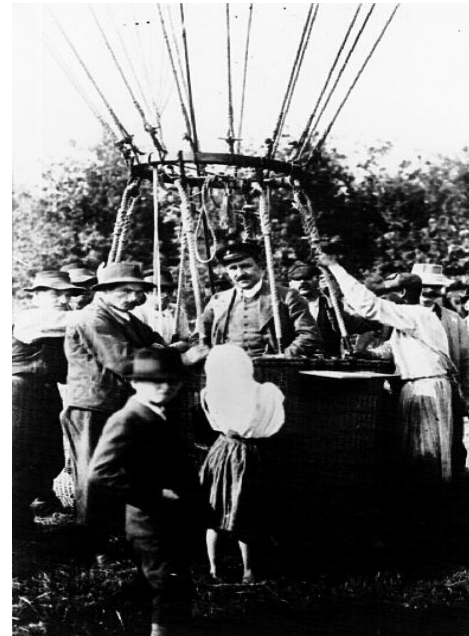


## 5.1.3 Weitere Teilchen in der kosmischen Strahlung



**V. Hess (1912)**

***Untersuchung der kosmischen Strahlung***



- Ballon-Experimente oder
- Photoplatten in großer Höhe (Berge)

1937: Anderson und Nedermeyer entdecken ein neues Teilchen X in der kosmischen Strahlung

$$m_X = 105 \text{ MeV} / c^2$$

Ursprüngliche Assoziation als „Yukawa-Teilchen“  $\pi$  - Meson (mittlere Masse)  
(Austauschteilchen der starken Wechselwirkung,  
Idee: Erklärung der kurzen Reichweite der starken Wechselwirkung durch  
Austausch eines massiven Teilchens)

heute:  $X \neq \pi$      $X = \mu$

**Myon: schwere Ausgabe des Elektrons**  
( $Q = \pm 1e$ , Spin  $\frac{1}{2} \hbar$ ,  $m = 105,7 \text{ MeV}/c^2$ )

***Wozu ?? „who ordered that ??“***

Klarstellung 1946 in Rom: Das X-Teilchen der kosmischen Strahlung wechselwirkt nur schwach mit Materie (d.h. mit Kernen) und kann demzufolge nicht mit dem Austauschteilchen der starken WW identisch sein.

Das Teilchen hat nur eine kurze Lebensdauer:  $\tau_\mu = 2,20 \cdot 10^{-6} \text{ sec}$   
 $c \tau_\mu = 659,1 \text{ m}$

1947: Powell et al. entdecken in Bristol ein zweites, mittelschweres Teilchen in der kosmischen Strahlung

Experiment: Photographische Emulsion auf Berghöhe

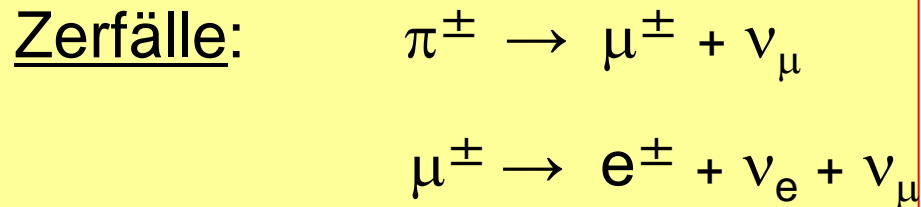
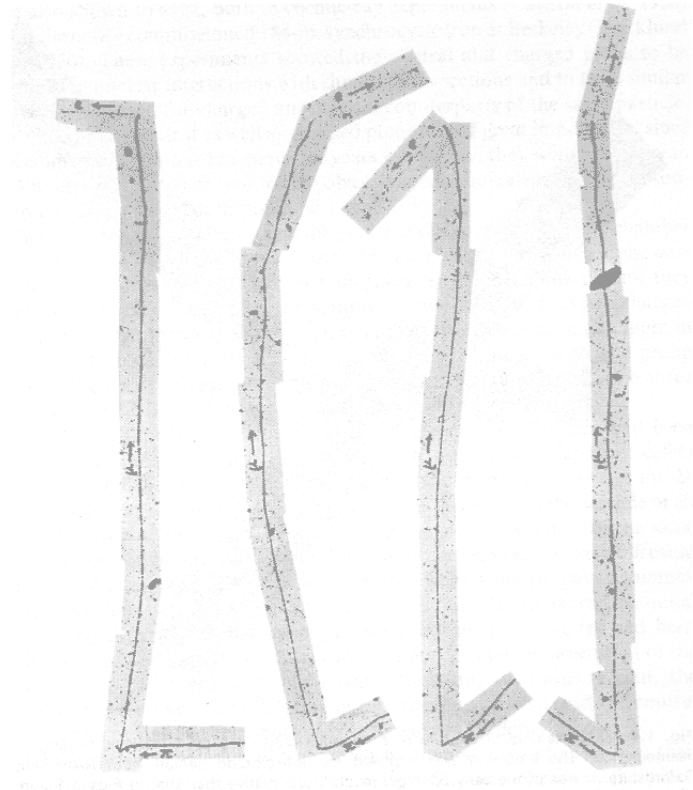
heutige Bezeichnung:  $\pi$  – Meson

$$m_{\pi} = 139,6 \text{ MeV}/c^2$$

$$\text{Lebensdauer: } \tau_{\pi} = 2,6 \cdot 10^{-8} \text{ sec}$$

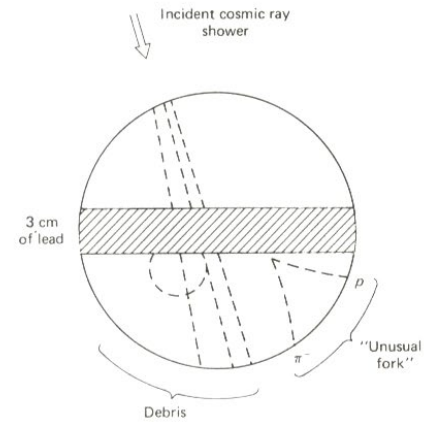
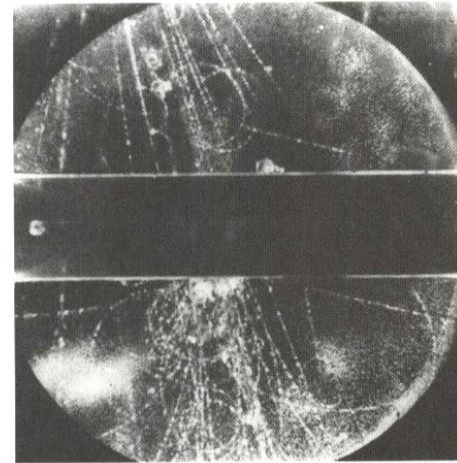
$\pi$ -Mesonen entstehen in der oberen Atmosphäre, zerfallen oder wechselwirken aber bevor sie den Erdboden erreichen

Rom: Meereshöhe → fast nur noch Myonen



## 5.1.4. Weitere, sog. Seltsame Teilchen

### *s. Vorlesung*



**Figure 1.8** The first strange particle. Cosmic rays strike a lead plate, producing a  $K^0$ , which subsequently decays into a pair of charged pions. (Photo courtesy of Prof. G. D. Rochester. Reprinted by permission from *Nature* **160**, 855. Copyright © 1947, Macmillan Journals Limited.)



**BARYONS (Spin 1/2)**

Baryon	Quark content	Charge	Mass	Lifetime	Principal decays
N { p n	uud	+1	938.280	$\infty$	—
	udd	0	939.573	900	$p\bar{e}\bar{\nu}_e$
$\Lambda$	uds	0	1115.6	$2.63 \times 10^{-10}$	$p\bar{\pi}^-, n\pi^0$
$\Sigma^+$	uus	+1	1189.4	$0.80 \times 10^{-10}$	$p\pi^0, n\pi^+$
$\Sigma^0$	uds	0	1192.5	$6 \times 10^{-20}$	$\Lambda\gamma$
$\Sigma^-$	dss	-1	1197.3	$1.48 \times 10^{-10}$	$n\pi^-$
$\Xi^0$	uss	0	1314.9	$2.90 \times 10^{-10}$	$\Lambda\pi^0$
$\Xi^-$	dss	-1	1321.3	$1.64 \times 10^{-10}$	$\Lambda\pi^-$
$\Lambda_c^+$	u $\bar{d}$ c	+1	2281	$2 \times 10^{-13}$	not established

**BARYONS (Spin 3/2)**

Baryon	Quark content	Charge	Mass	Lifetime	Principal decays
$\Delta$	uuu, uud, udd, ddd	+2, +1, 0, -1	1232	$0.6 \times 10^{-23}$	$N\pi$
$\Sigma^*$	uus, uds, dds	+1, 0, -1	1385	$2 \times 10^{-23}$	$\Lambda\pi, \Sigma\pi$
$\Xi^*$	uss, dss	0, -1	1533	$7 \times 10^{-23}$	$\Xi\pi$
$\Omega^-$	sss	-1	1672	$0.82 \times 10^{-10}$	$\Lambda K^-, \Xi^0\pi^-, \Xi^-\pi^0$

**PSEUDOSCALAR MESONS (Spin 0)**

Meson	Quark content	Charge	Mass	Lifetime	Principal decays
$\pi^\pm$	u $\bar{d}$ , d $\bar{u}$	+1, -1	139.569	$2.60 \times 10^{-8}$	$\mu\nu_\mu$
$\pi^0$	(u $\bar{u}$ - d $\bar{d}$ )/ $\sqrt{2}$	0	134.964	$8.7 \times 10^{-17}$	$\gamma\gamma$
$K^\pm$	u $\bar{s}$ , s $\bar{u}$	+1, -1	493.67	$1.24 \times 10^{-8}$	$\mu\nu_\mu, \pi^+\pi^0, \pi^+\pi^-\pi^0$
$K^0, \bar{K}^0$	d $\bar{s}$ , s $\bar{d}$	0, 0	497.72	$\left\{ \begin{array}{l} K_S^0: 0.892 \times 10^{-10} \\ K_L^0: 5.18 \times 10^{-8} \end{array} \right.$	$\pi^+\pi^-, \pi^0\pi^0$
$\eta$	(u $\bar{u}$ + d $\bar{d}$ - 2s $\bar{s}$ )/ $\sqrt{6}$	0	548.8	$7 \times 10^{-19}$	$\pi e\nu_e, \pi\mu\nu_\mu, \pi\pi\pi$
$\eta'$	(u $\bar{u}$ + d $\bar{d}$ + s $\bar{s}$ )/ $\sqrt{3}$	0	957.6	$3 \times 10^{-21}$	$\gamma\pi\pi, \rho^0\gamma$
$D^\pm$	c $\bar{d}$ , d $\bar{c}$	+1, -1	1869	$9 \times 10^{-13}$	$K\pi\pi$
$D^0, \bar{D}^0$	c $\bar{u}$ , u $\bar{c}$	0, 0	1865	$4 \times 10^{-13}$	$K\pi\pi$
$F^\pm$ (now $D_s^\pm$ )	c $\bar{s}$ , s $\bar{c}$	+1, -1	1971	$3 \times 10^{-13}$	not established
$B^\pm$	u $\bar{b}$ , b $\bar{u}$	+1, -1	5271	$14 \times 10^{-13}$	$D + ?$
$B^0, \bar{B}^0$	d $\bar{b}$ , b $\bar{d}$	0, 0	5275		
$\eta_c$	c $\bar{c}$	0	2981		

**VECTOR MESONS (Spin 1)**

Meson	Quark content	Charge	Mass	Lifetime	Principal decays
$\rho$	u $\bar{d}$ , d $\bar{u}$ , (u $\bar{u}$ - d $\bar{d}$ )/ $\sqrt{2}$	+1, -1, 0	770	$0.4 \times 10^{-23}$	$\pi\pi$
$K^*$	u $\bar{s}$ , s $\bar{u}$ , d $\bar{s}$ , s $\bar{d}$	+1, -1, 0, 0	892	$1 \times 10^{-23}$	$K\pi$
$\omega$	(u $\bar{u}$ + d $\bar{d}$ )/ $\sqrt{2}$	0	783	$7 \times 10^{-23}$	$\pi^+\pi^-\pi^0, \pi^0\gamma$
$\phi$	s $\bar{s}$	0	1020	$20 \times 10^{-23}$	$K^+K^-, K^0\bar{K}^0$
$J/\psi$	c $\bar{c}$	0	3097	$1 \times 10^{-20}$	$e^+e^-, \mu^+\mu^-, 5\pi, 7\pi$
$D^*$	c $\bar{d}$ , d $\bar{c}$ , c $\bar{u}$ , u $\bar{c}$	+1, -1, 0, 0	2010	$>1 \times 10^{-22}$	$D\pi, D\gamma$
$\Upsilon$	b $\bar{b}$	0	9460	$2 \times 10^{-20}$	$\tau^+\tau^-, \mu^+\mu^-, e^+e^-$

**PARTICLE DATA**  
(Mass in MeV/c<sup>2</sup>; Lifetime in Seconds; Charge in Units of Proton Charge.)

**QUARKS (Spin 1/2)**

Flavor	Charge	Mass (speculative)		
		Bare	Effective	
			In baryons	In mesons
First generation { d u	$-\frac{1}{3}$ $+\frac{2}{3}$	7.5 4.2	363	310
Second generation { s c	$-\frac{1}{3}$ $+\frac{2}{3}$	150 1100		
Third generation { b t	$-\frac{1}{3}$ $+\frac{2}{3}$	4200	1500 4700	$\sim 173.000$

**LEPTONS (Spin 1/2)**

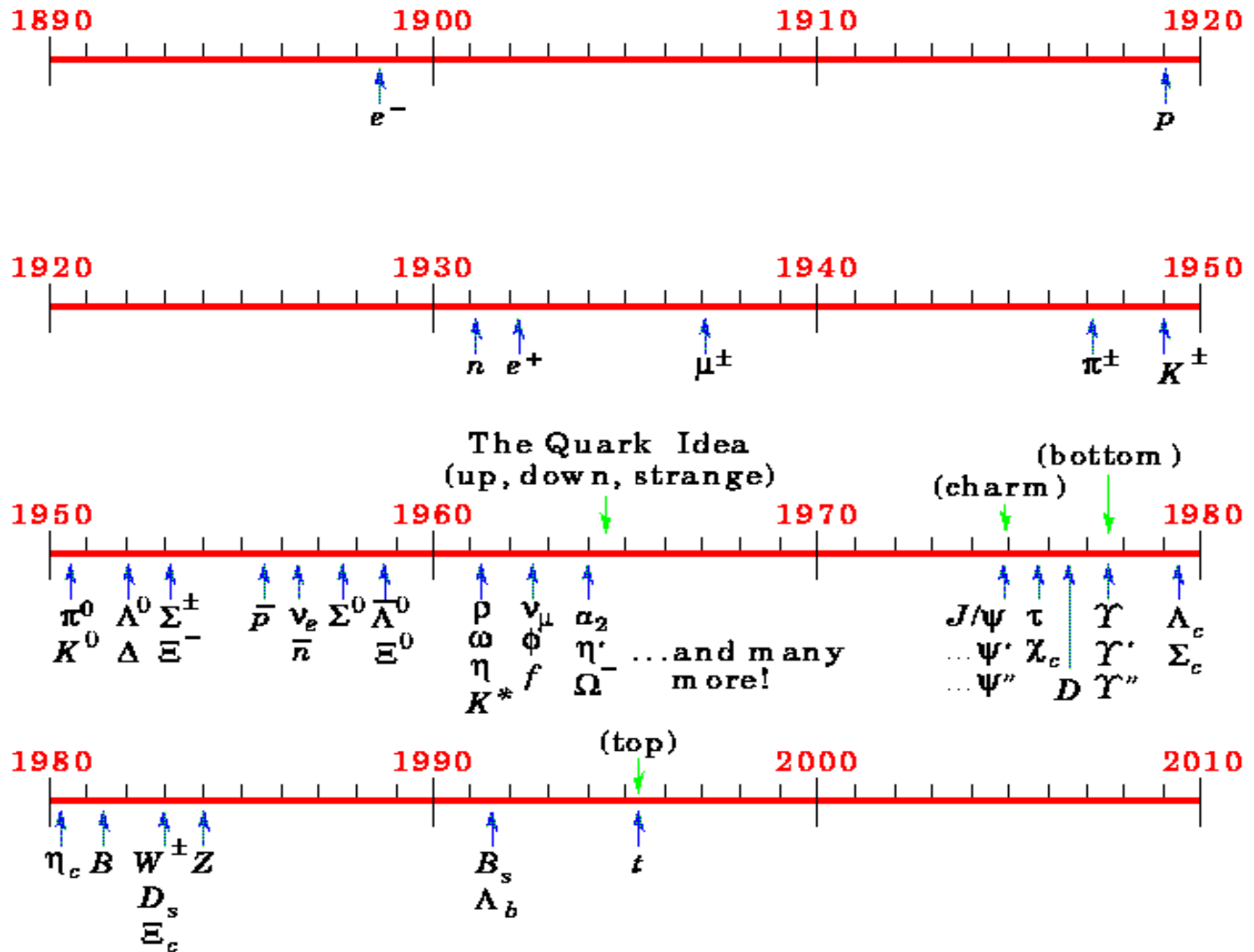
Lepton	Charge	Mass	Lifetime	Principal decays
First generation { e $\nu_e$	-1 0	0.511003 0	$\infty$ $\infty$	— —
Second generation { $\mu$ $\nu_\mu$	-1 0	105.659 0	$2.197 \times 10^{-6}$ $\infty$	$e\nu_\mu\bar{\nu}_e$ —
Third generation { $\tau$ $\nu_\tau$	-1 0	1784 0	$3.3 \times 10^{-13}$ $\infty$	$\mu\nu_\tau\bar{\nu}_\mu, e\nu_\tau\bar{\nu}_e, \rho\nu_\tau$ —

**MEDIATORS (Spin 1)**

Mediator	Charge	Mass	Lifetime	Force
gluon	0	0	$\infty$	strong
photon ( $\gamma$ )	0	0	$\infty$	
$W^\pm$	$\pm 1$	81,800	unknown	(charged) weak
$Z^0$	0	92,600	unknown	



# 5.1.5. Entdeckte Teilchen



## 5.2 Additive Quantenzahlen

zur Charakterisierung von Teilchen

### LEPTON CLASSIFICATION

	$l$	$Q$	$L_e$	$L_\mu$	$L_\tau$
First generation	$e$	-1	1	0	0
	$\nu_e$	0	1	0	0
Second generation	$\mu$	-1	0	1	0
	$\nu_\mu$	0	0	1	0
Third generation	$\tau$	-1	0	0	1
	$\nu_\tau$	0	0	0	1

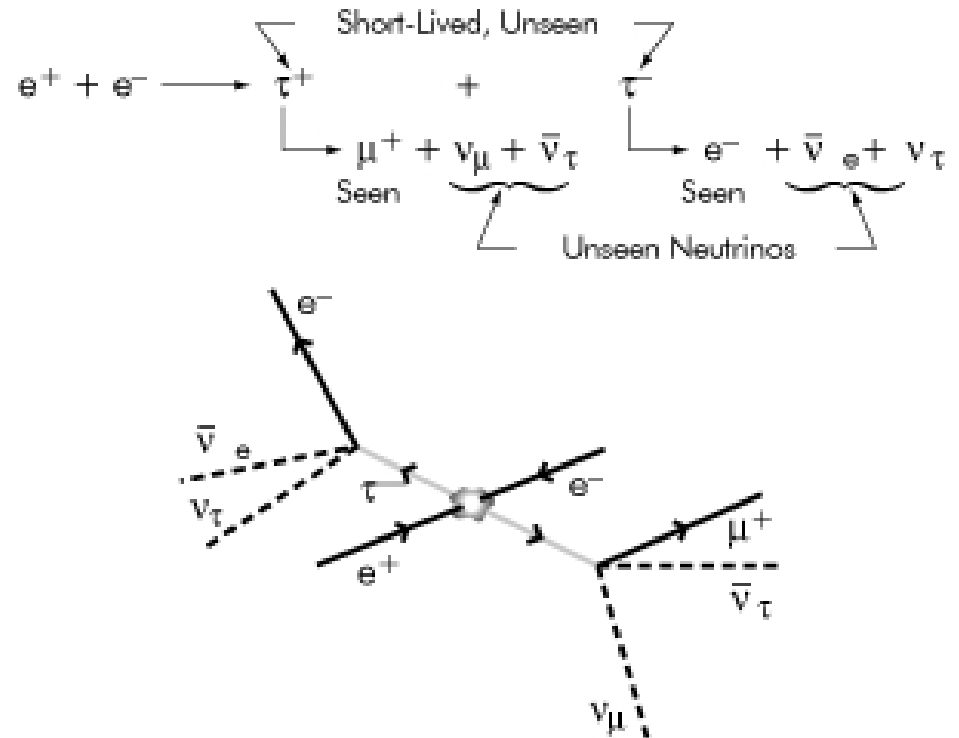
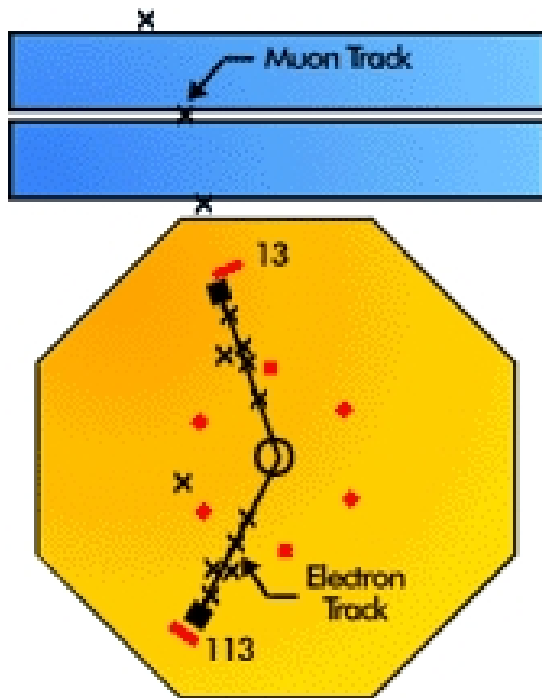
## 5.3 Teilchen–Antiteilchen Reaktionen

## 5.4 Leptonen

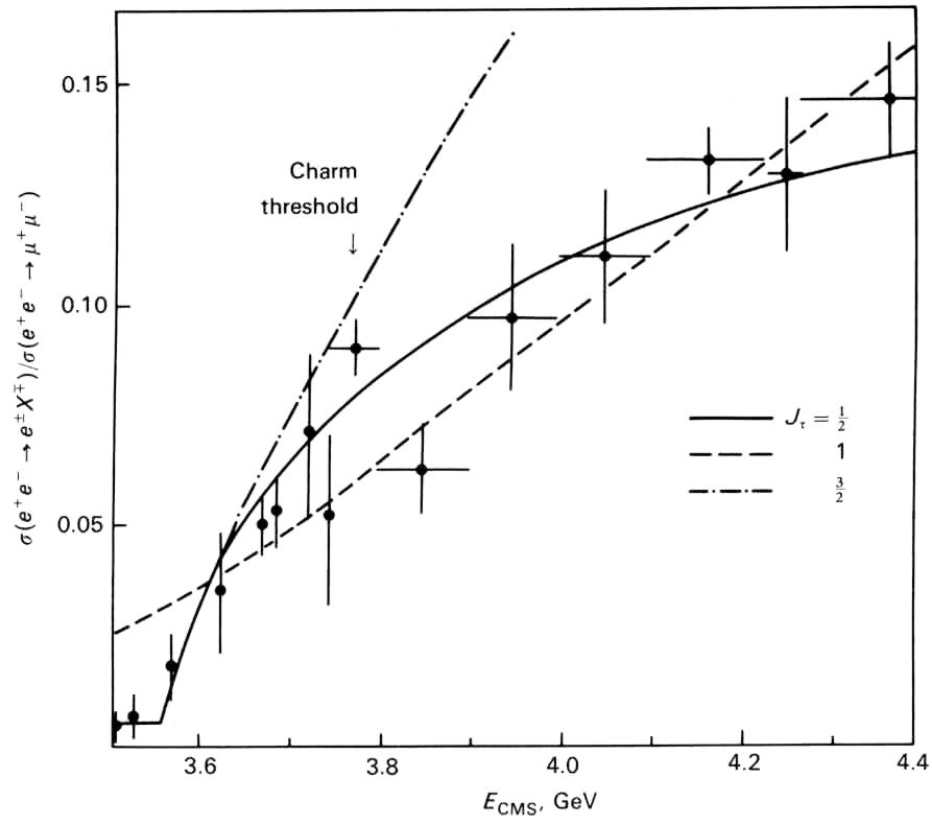
# Die Entdeckung des $\tau$ -Leptons

1975: Stanford Linear Accelerator Center, SLAC, M. Perl  
 Studium von  $e^+e^-$  Kollisionen mit dem MARK-I Detektor am  
 Speicherring SPEAR (Strahlenergie 4 GeV)

Entdeckung eines neuen, schweren Leptons  
 Tau-Lepton,  $m(\tau) = 1.78 \text{ GeV}/c^2$







Analysis of  $\tau$ -lepton production by DELCO collaboration at SLAC  $e^+e^-$  collider SPEAR (Bacino *et al.* 1978). Pair production of  $\tau$ -leptons is recognized as events consisting of one electron track, and one other track due to a muon or hadron, of opposite sign of charge. The data clearly favor spin- $\frac{1}{2}$  for the  $\tau$ .

(aus Ref. [8])

# Experimenteller Nachweis des Neutrinos

1956: C.L. Cowan und F. Reines,

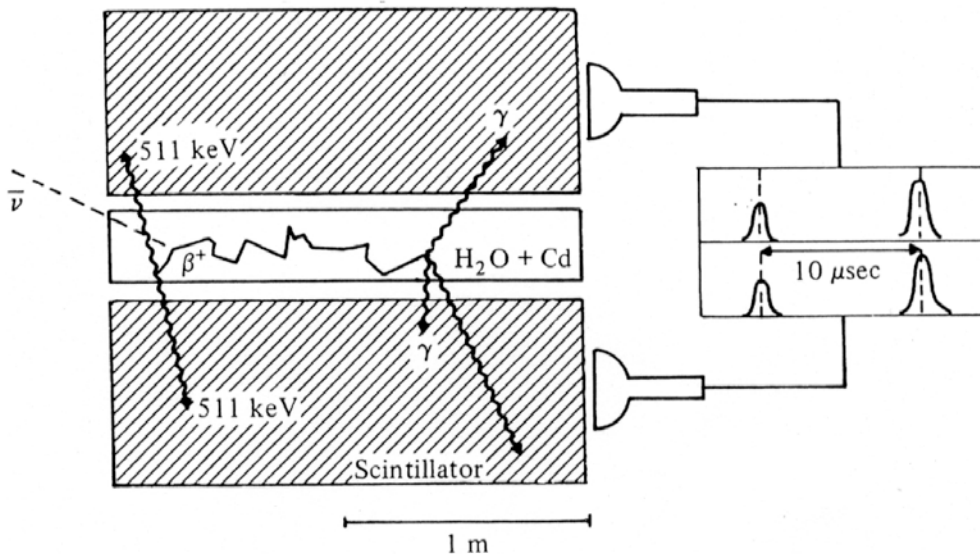
Neutrinoquelle: Kernreaktor (Savannah River, South Carolina, USA)

Nachweisreaktion: Inverser  $\beta$ -Zerfall  $\bar{\nu}_e + p \rightarrow n + e^+$

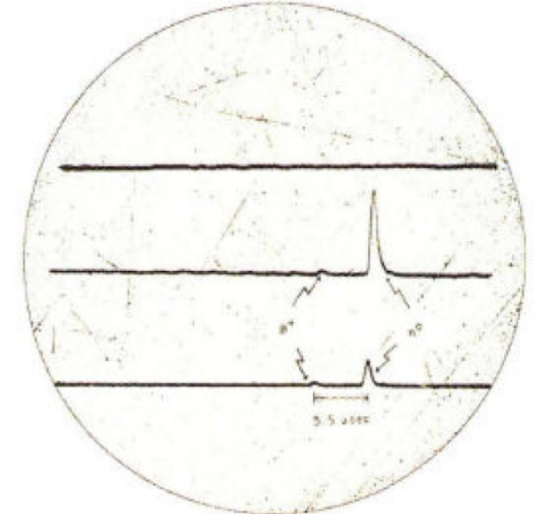
Abstand zum Detektor: 11 m, Neutrinofluss:  $5 \cdot 10^{13} \text{ cm}^{-2} \text{ sec}^{-1}$

Detektor: Flüssigszintillator mit Photomultiplier

- Promptes Signal:  $e^+ + e^- \rightarrow \gamma\gamma$
- Verzögertes Signal:  $n + {}^{108}\text{Cd} \rightarrow {}^{109}\text{Cd}^* \rightarrow {}^{109}\text{Cd} + \gamma$

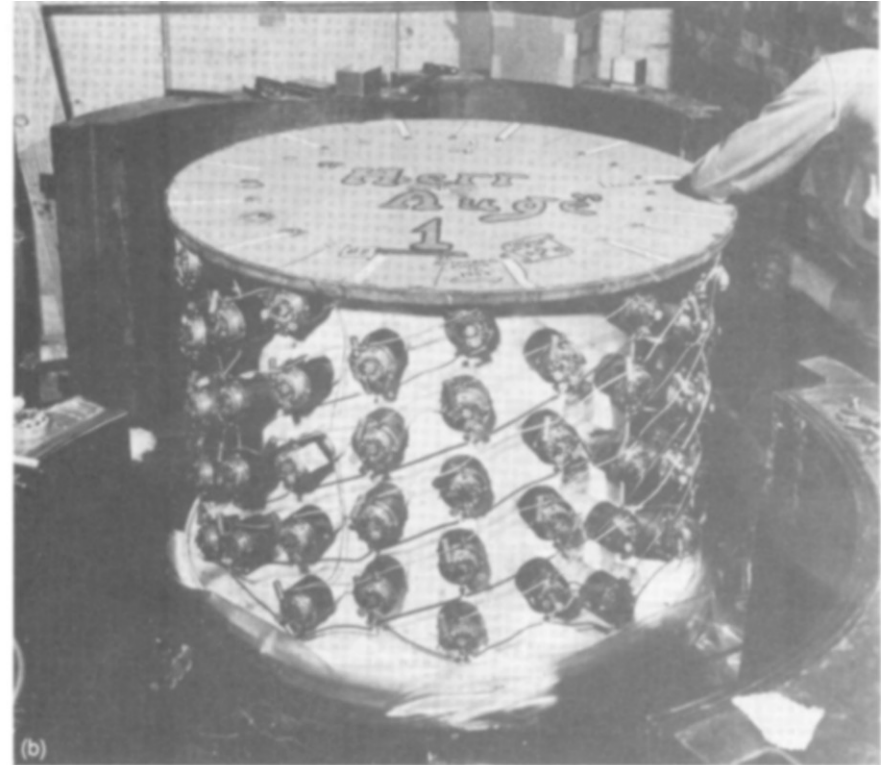


Das erste Neutrinosignal

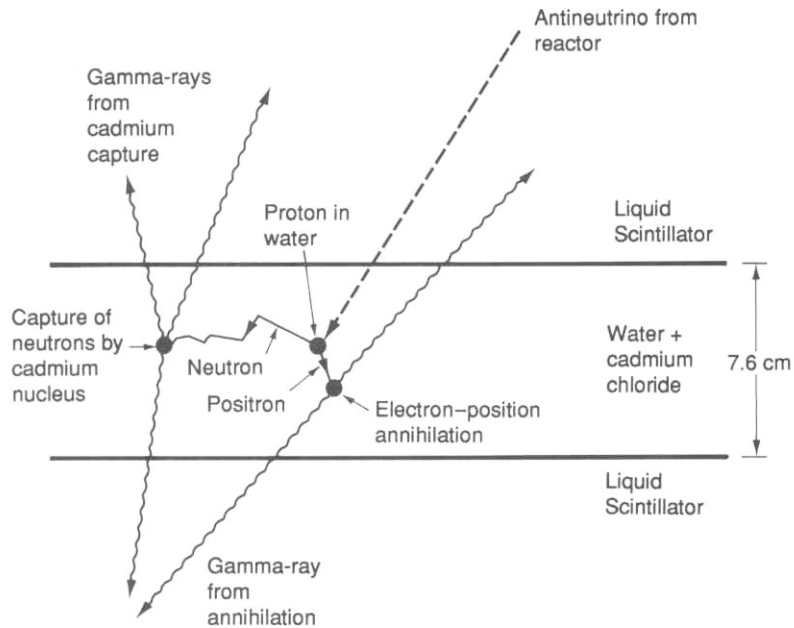




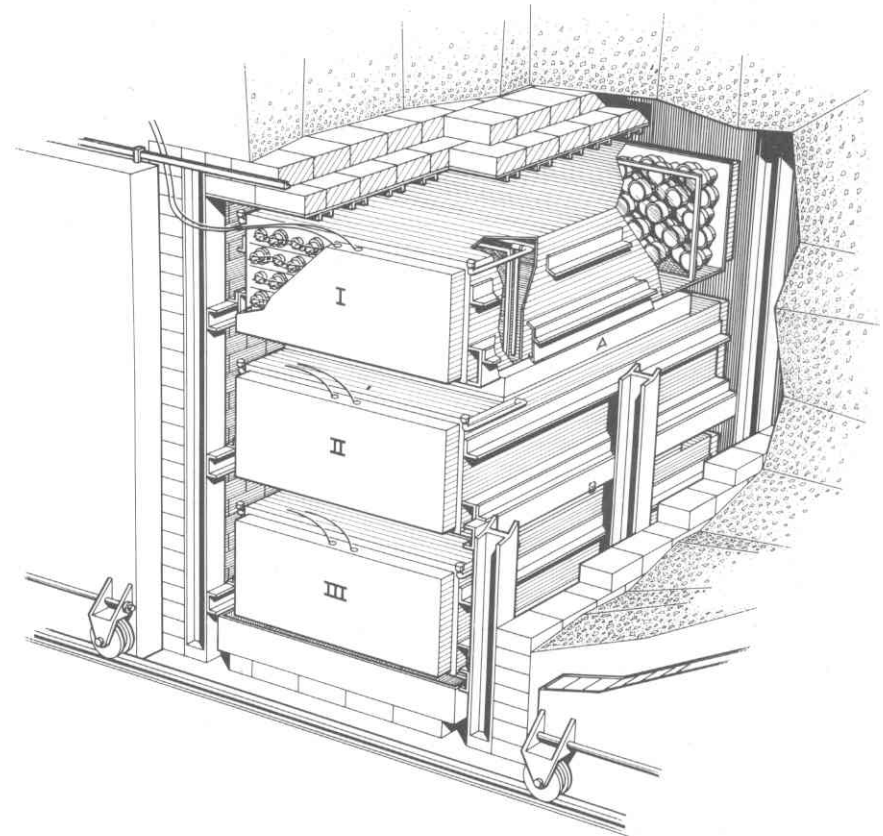
Clyde Cowan (far left) and Fred Raines (far right) with their team on 'Project Poltergeist', the prototype neutrino detector that demonstrated the potential of the technique they had chosen.



The detector itself - a 300-litre tank of liquid scintillator, surrounded by 90 phototubes. Before this, 20 litres of liquid had seemed a large volume!  
(Los Alamos National Laboratory)

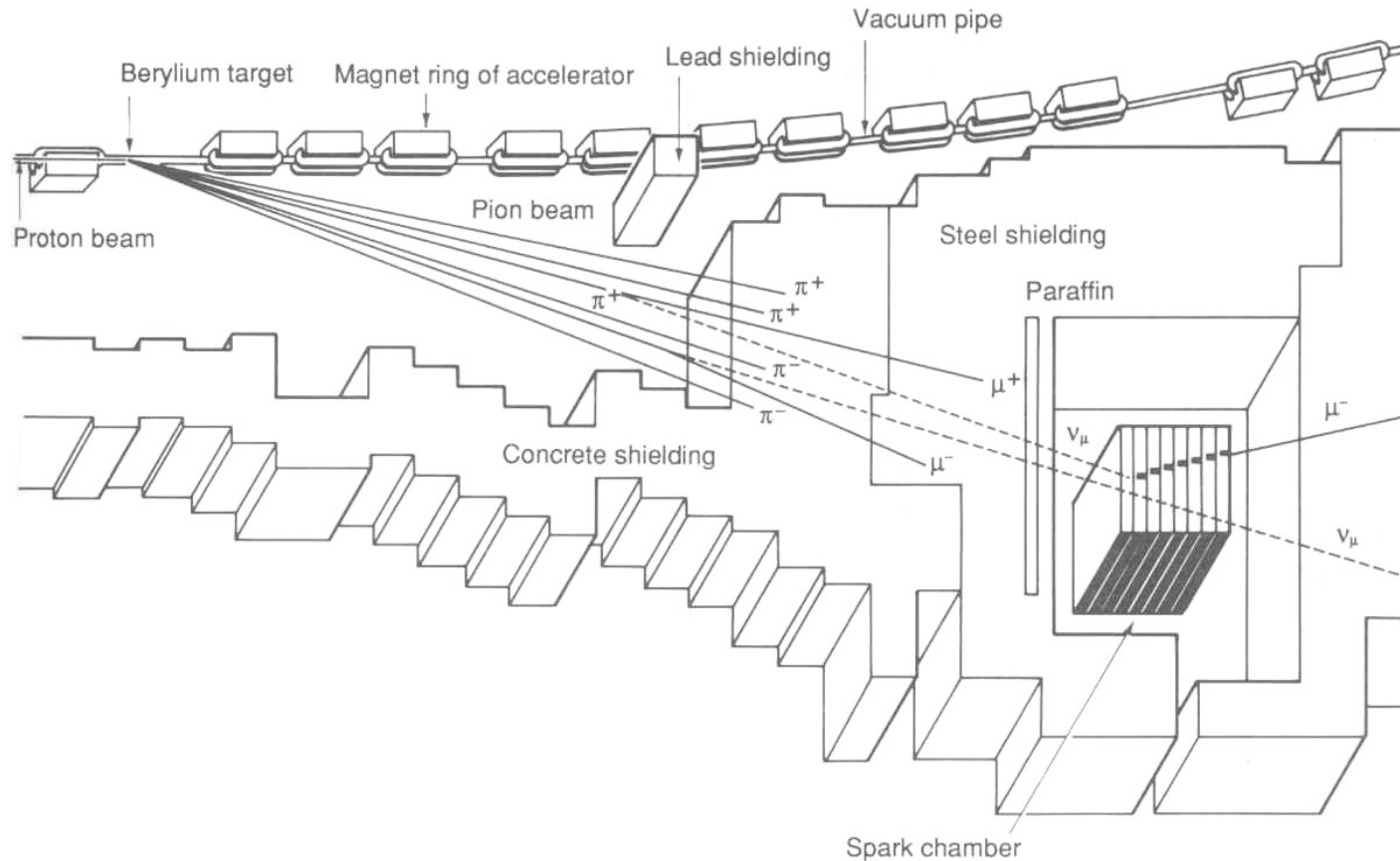


The method Reines and Cowan used finally to detect neutrinos was a three-step process: first a proton in the water would absorb a neutrino, and produce a neutron and a positron; then almost immediately the positron would annihilate with an electron, emitting two back-to-back gamma-rays which could be detected in the adjacent layers of scintillator; and lastly, some 5 microseconds or so after the annihilation gamma-rays had emerged, the neutron would be captured by a cadmium nucleus, which would then emit some more gamma-rays.



The final assembly of Cowan and Reines used to detect neutrinos from the powerful nuclear reactor at Savannah River, South Carolina. The large tanks labelled I, II and III contained liquid scintillator, and were each viewed by 110 phototubes; the smaller ones sandwiched between, labelled A and B, contained water with cadmium chloride dissolved in it. (*Physical Review*, **117**, 160, 1960.)

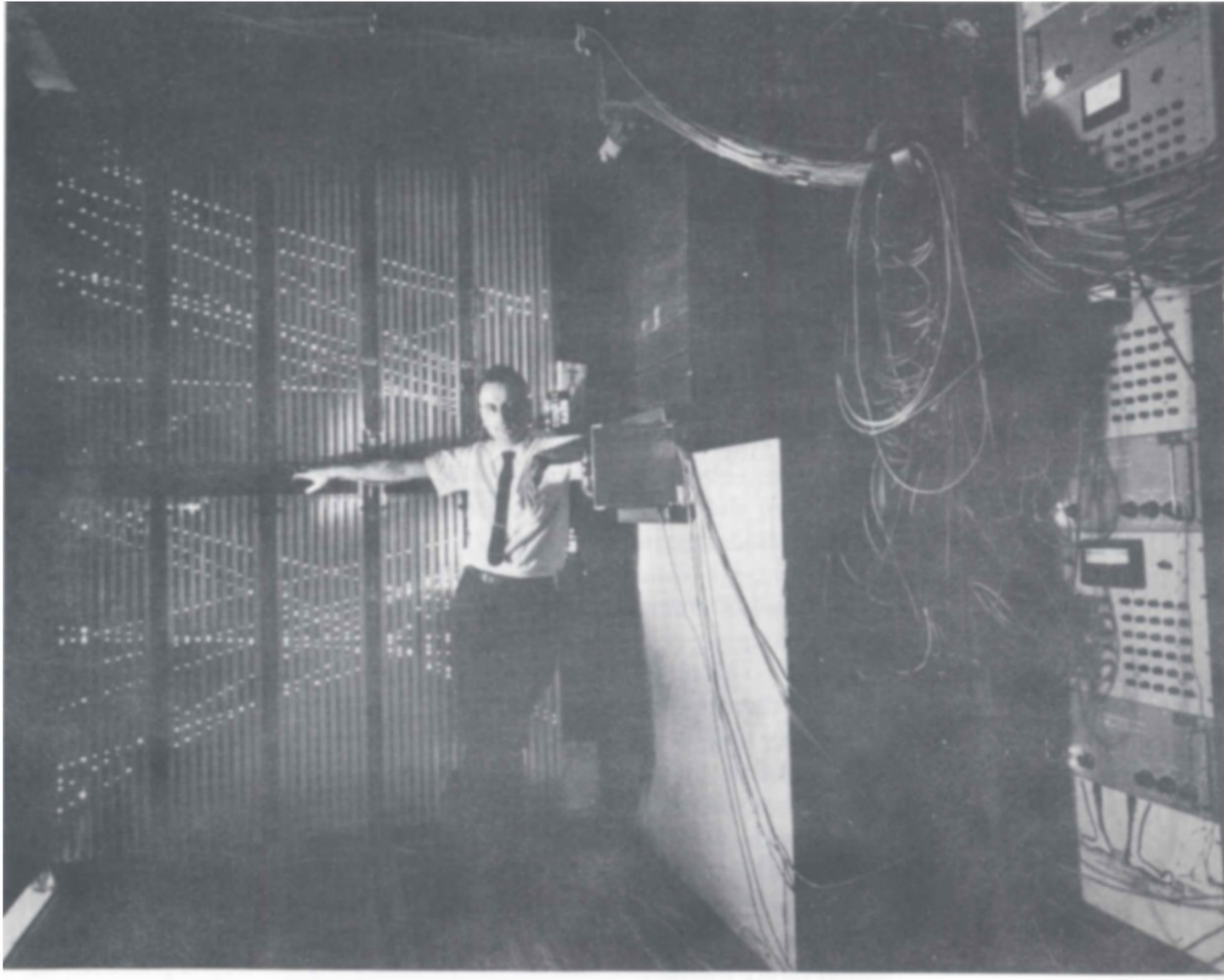
# Nachweis $\nu_\mu \neq \nu_e$ (1962)



The principle of the first high-energy neutrino experiment at Brookhaven was to create the neutrinos in the decays of pions produced when protons in the accelerator struck a target of beryllium. Large amounts of steel shielding in a wall 13.5 meters thick absorbed both the muons produced and the remaining pions, allowing only the neutrinos to penetrate to the 10-tonne spark chamber.



Steinberger (links),  
Ledermann (2ter von rechts),  
Schwartz (rechts) et al.

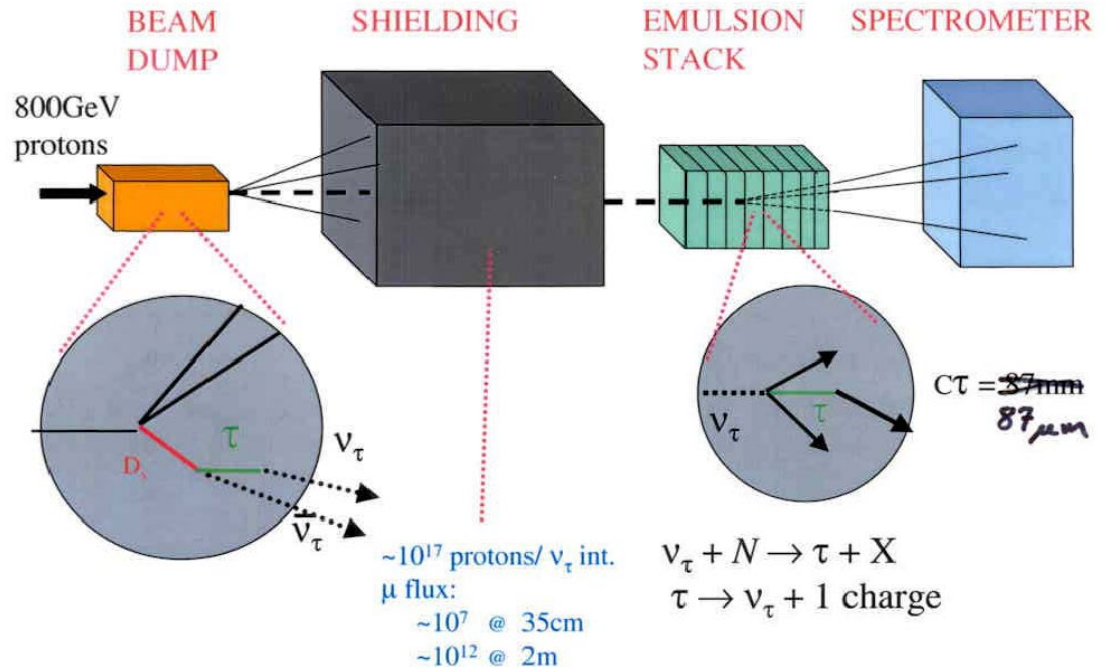
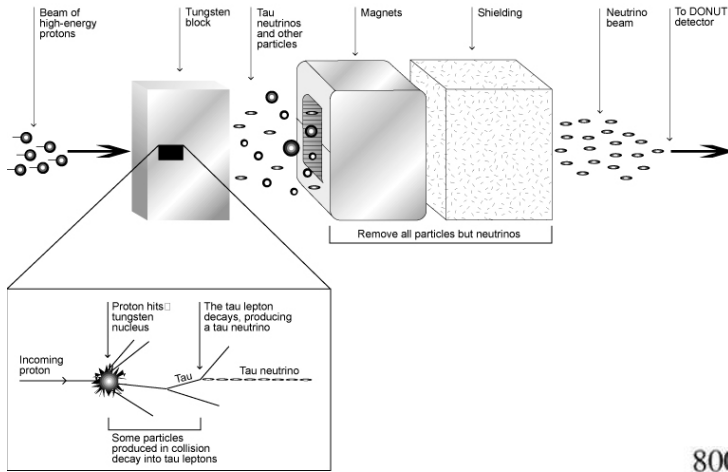


Mel Schwartz standing in front of the 10-tonne spark chamber used in the 'two-neutrino experiment'. Each of the ten modules contains 1 ton of aluminium in the form of nine plates which are 2.5 centimeters thick and separated by a gas-filled gap of 1 centimeter. High voltage across the plates causes the gas to spark along the tracks of charged particles, which, in this time-lapse picture, are cosmic rays. (Brookhaven National Laboratory.)



# Experimenteller Nachweis des $\nu_\tau$ (2000)

## Creating a Tau Neutrino Beam





## 5.5 Das Quark-Modell

## Können alle diese Teilchen elementar sein ??

1964: **Quark-Hypothese**



vorgeschlagen von **M. Gell-Mann** und **G. Zweig** (unabhängig voneinander)  
(Theoretisches Konzept, drittel-zahlige elektrische Ladungen)

Hauptmotivation: Teilchenvielfalt  $\Rightarrow$  **neue Substruktur**

zum Aufbau aller bekannten Teilchen waren  
3 Quarks notwendig  
(up-Quark, down-Quark und strange-Quark)

Experimentelle Bestätigung: Ende der 60er / Beginn der 70er Jahre  
des letzten Jahrhunderts

**„- THREE *QUARKS* FOR MUSTER MARK !  
SURE HE HASN´T GOT MUCH OF A BARK  
AND SURE ANY HE HAS IT´S ALL BESIDE THE  
MARK.  
BUT O WRENEAGLE ALMIGHTY WOULDN´T UN  
BE A SKY OF A LARK  
TO SEE THAT OLD BUZZARD ABOUT FOR UNS  
SHIRT IN THE DARK  
AND HE HUNTING ROUND FOR UNS SPECKLED  
TROUSERS AROUND BY PALMERSTOWN PARK?“**

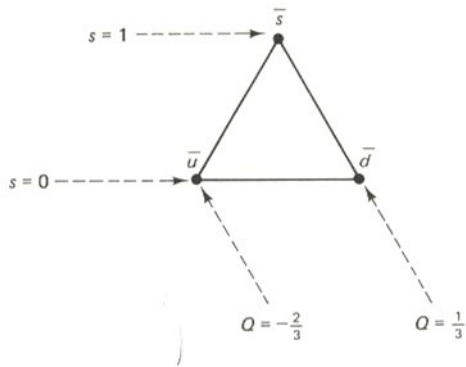
**aus Finnegans Wake, von James Joyce**

THE MESON NONET

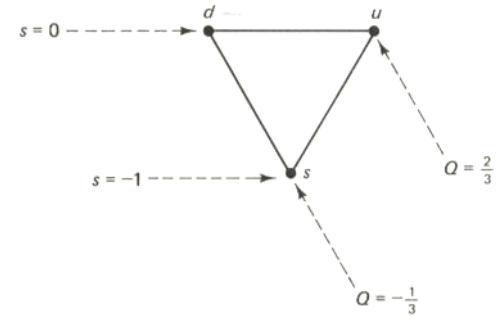
$q\bar{q}$	Q	S	Meson
$u\bar{u}$	0	0	$\pi^0$
$u\bar{d}$	1	0	$\pi^+$
$d\bar{u}$	-1	0	$\pi^-$
$d\bar{d}$	0	0	$\eta$
$u\bar{s}$	1	1	$K^+$
$d\bar{s}$	0	1	$K^0$
$s\bar{u}$	-1	-1	$K^-$
$s\bar{d}$	0	-1	$\bar{K}^0$
$s\bar{s}$	0	0	??

THE BARYON DECUPLET

$qqq$	Q	S	Baryon
$uuu$	2	0	$\Delta^{++}$
$uud$	1	0	$\Delta^+$
$udd$	0	0	$\Delta^0$
$ddd$	-1	0	$\Delta^-$
$uus$	1	-1	$\Sigma^{*+}$
$uds$	0	-1	$\Sigma^{*0}$
$dds$	-1	-1	$\Sigma^{*-}$
$uss$	0	-2	$\Xi^{*0}$
$dss$	-1	-2	$\Xi^{*-}$
$sss$	-1	-3	$\Omega^-$

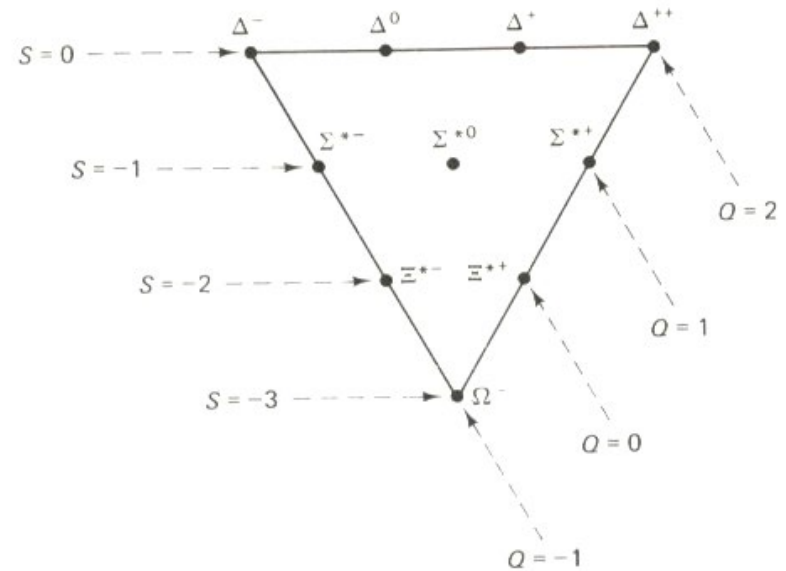
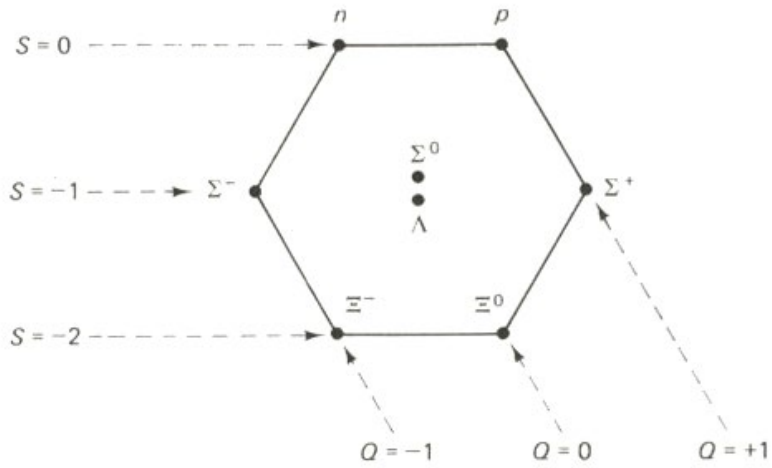


Die Bausteine:  
Quarks und Antiquarks



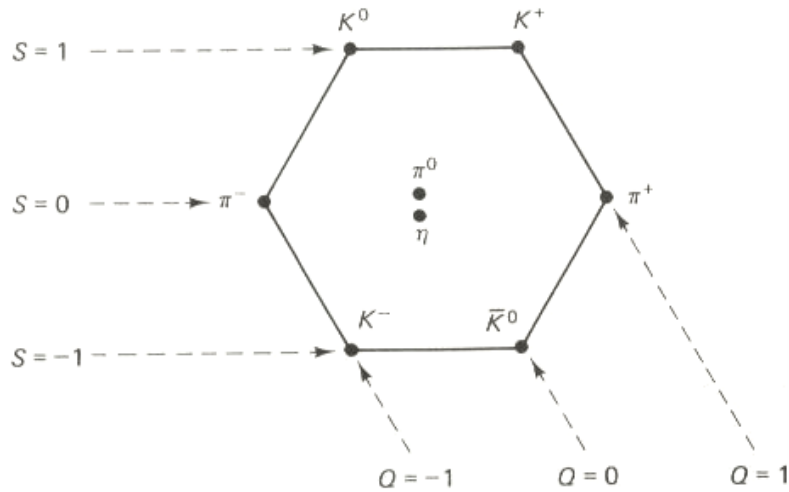


# Das Quark-Modell



## Das Baryonen-Oktett

## Das Baryonen-Dekuplett



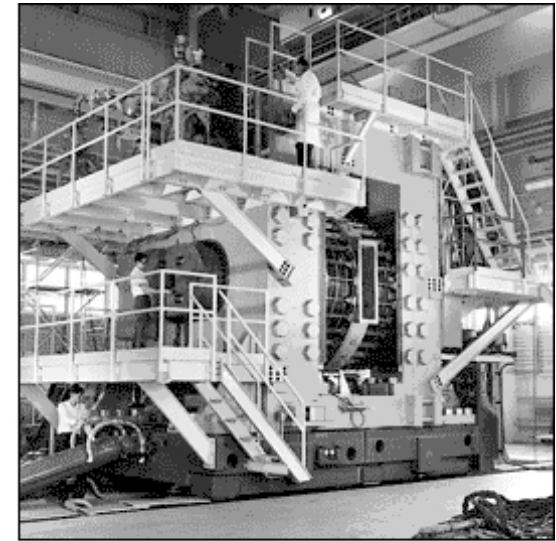
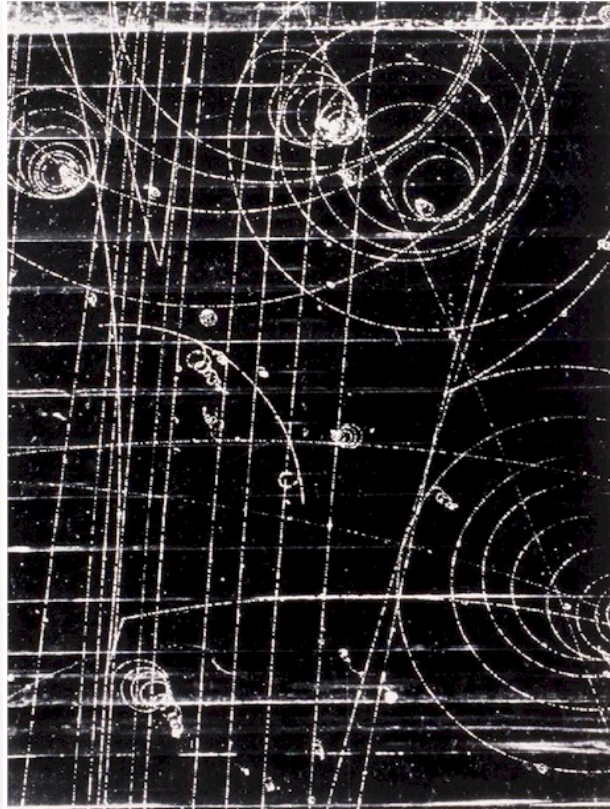
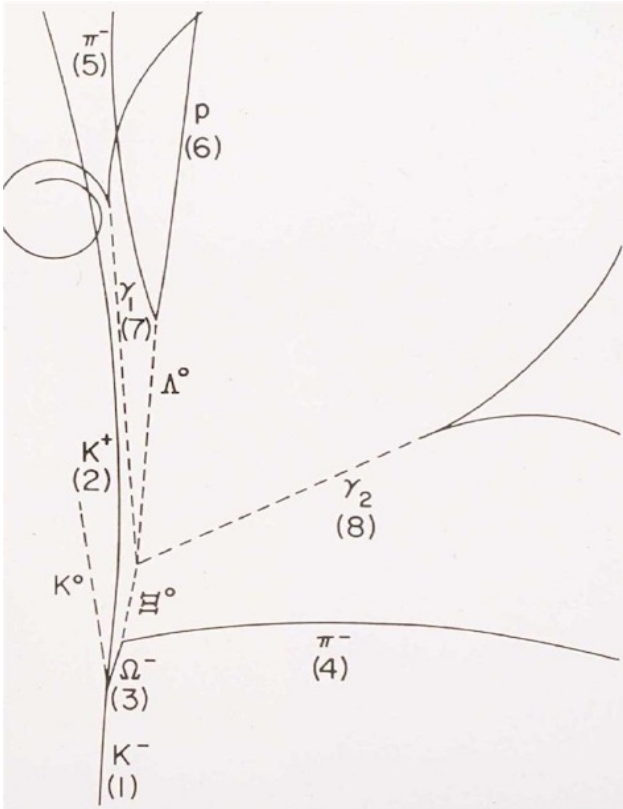
## Das Mesonen-Oktett

# Die Entdeckung des $\Omega^-$

1964: Brookhaven, AGS-Beschleuniger  
80 Zoll Blasen-kammer, flüssiger Wasserstoff

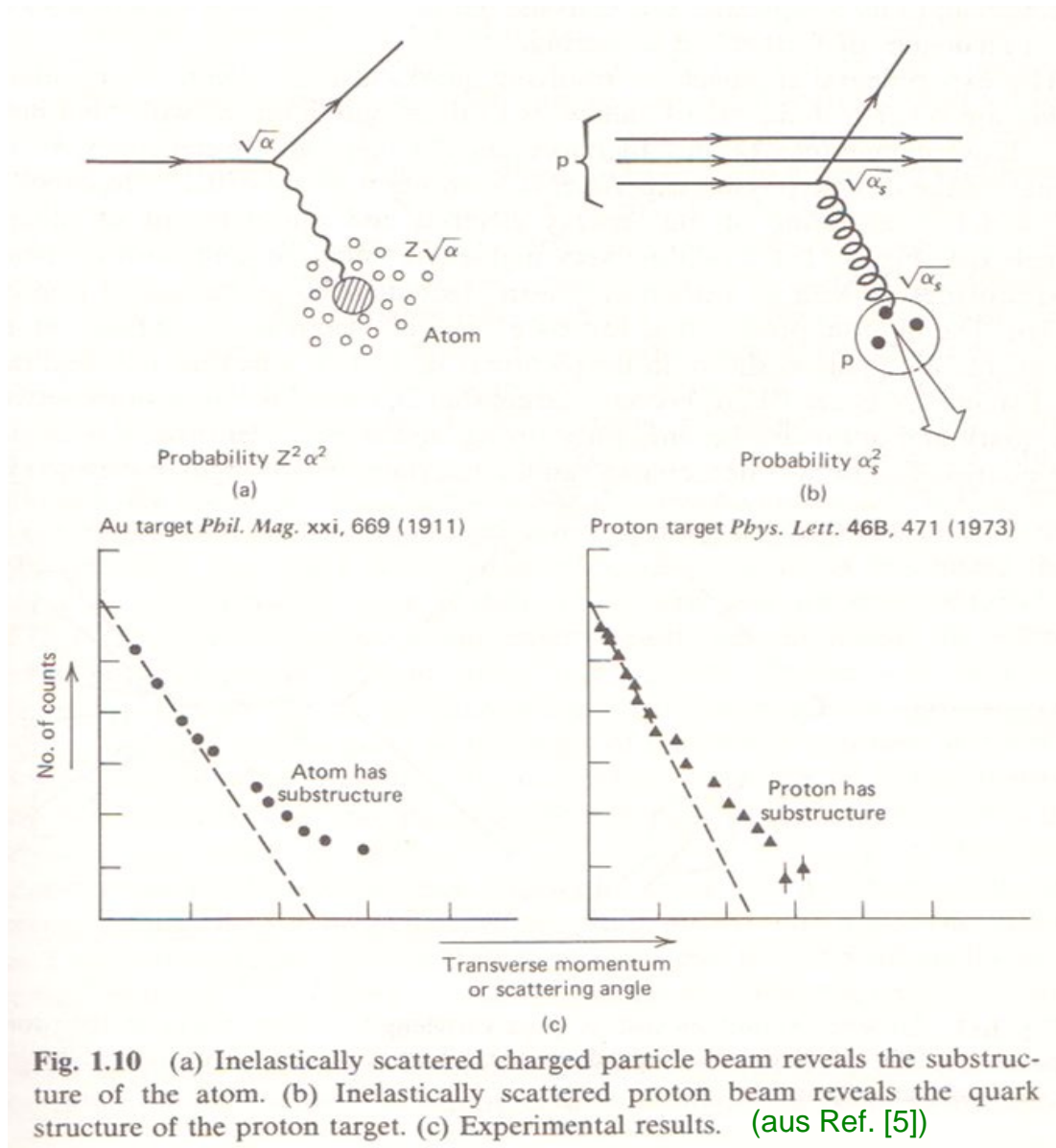
Beobachtung der Reaktion  $K^- + p \rightarrow K^0 K^+ \Omega^-$

Strangeness  $S = -3$ , (sss), Kaskadenzerfälle  
Neues Teilchen,  $m(\Omega) = 1.672 \text{ GeV}/c^2$



The 80-inch Bubble Chamber

# Experimentelle Evidenz für Quarks



**Fig. 1.10** (a) Inelastically scattered charged particle beam reveals the substructure of the atom. (b) Inelastically scattered proton beam reveals the quark structure of the proton target. (c) Experimental results. (aus Ref. [5])

## 5.6 Neue, schwere Quarks

# Entdeckung der cc-Resonanzen (J/ψ) (1974)

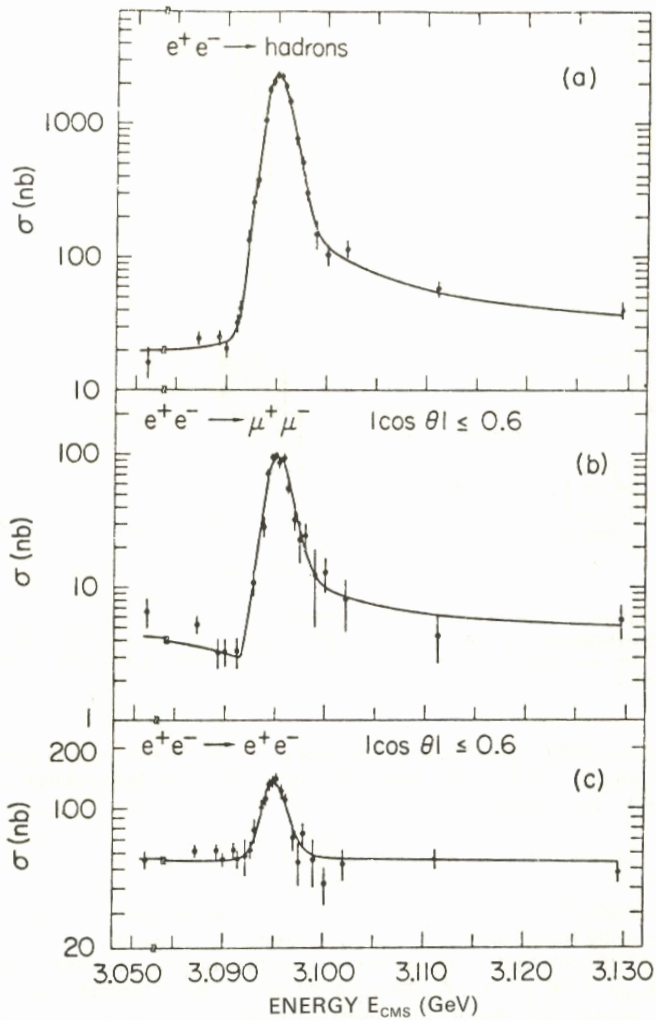


Fig. 5.10 Results of Augustin *et al.* (1974) showing the observation of the  $\psi/J$  resonance of mass 3.1 GeV, produced in  $e^+e^-$  annihilation at the SPEAR storage ring, SLAC.

(aus Ref. [8])

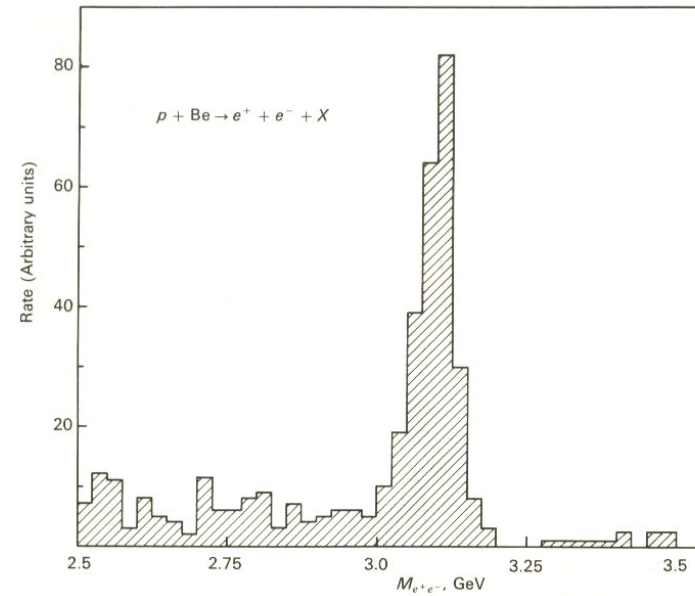
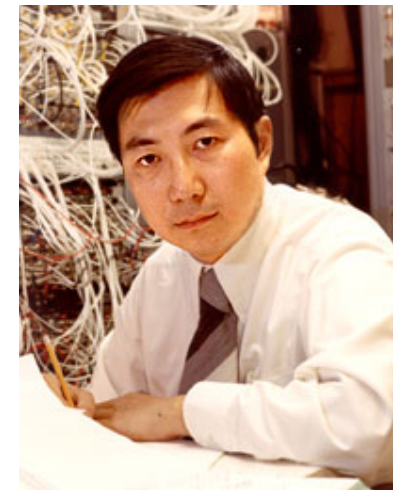
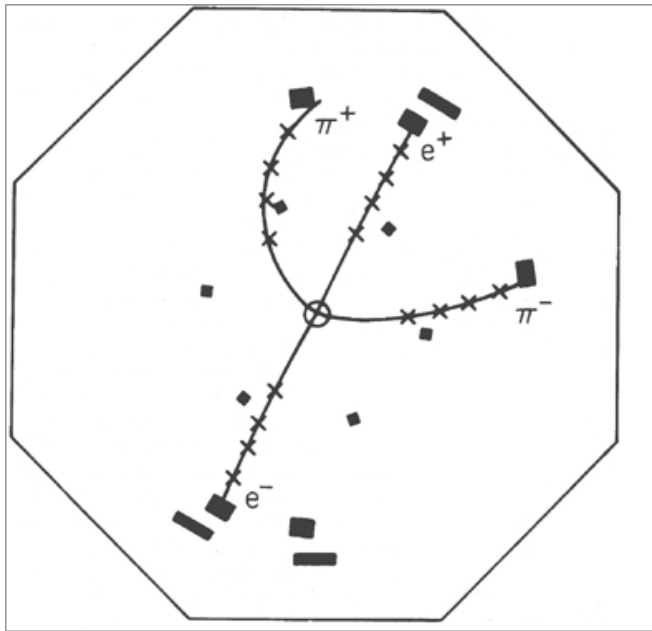


Fig. 5.11 Results of Aubert *et al.* (1974) indicating the narrow resonance  $\psi/J$  in the invariant-mass distribution of  $e^+e^-$  pairs produced in inclusive reactions of protons with a beryllium target. The experiment was carried out with the 28-GeV AGS at Brookhaven National Laboratory.

(aus Ref. [8])



Samuel S. Ting (1974)



Beobachteter Zerfall  $\psi' \rightarrow J/\psi \pi^+\pi^- \rightarrow e^+e^- \pi^+\pi^-$   
 (aus Ref. [8])

TABLE 5.7 Charmonium states and decay modes (aus Ref. [8])

State	Mass, MeV	$J^P, I$	$\Gamma$ , MeV	Branching ratio	
$J/\psi(3100)$	$3097 \pm 1$	$1^-, 0$	0.063	Hadrons [mostly $(2n + 1)\pi$ ]	86%
				$e^+e^-$	7%
				$\mu^+\mu^-$	7%
$\psi(3700)$	$3685 \pm 1$	$1^-, 0$	0.228	$\psi + 2\pi$	50%
				$\chi + \gamma$	21%
				$e^+e^-$	0.9%
				$\mu^+\mu^-$	0.9%



# Entdeckung der $\psi$ -Resonanzen ( $\Upsilon$ ) (1977)

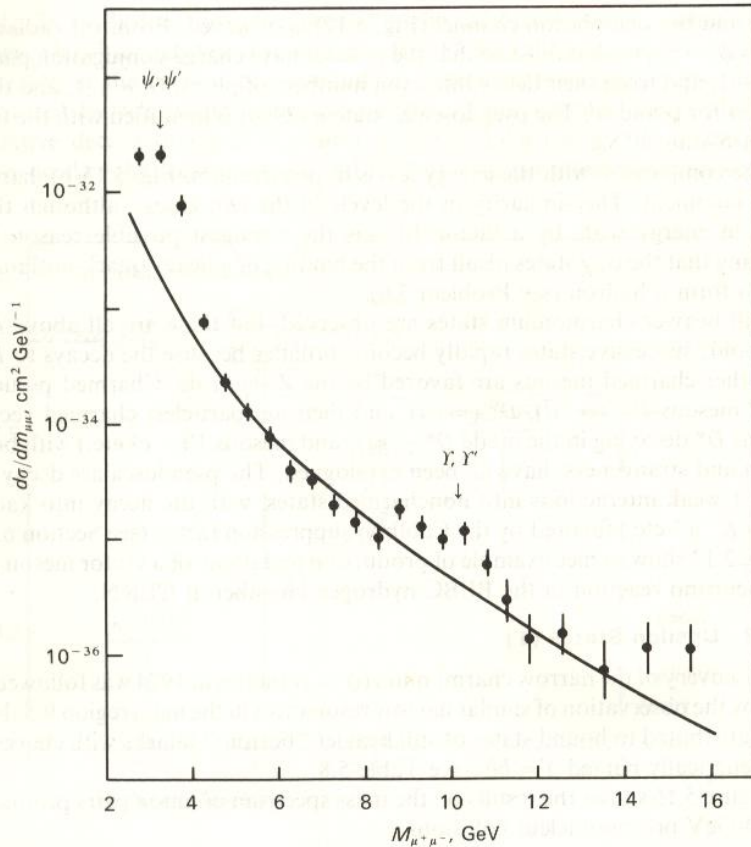


Fig. 5.16 First evidence for the upsilon resonances  $\Upsilon, \Upsilon'$ , obtained by Herb *et al.* (1977) from the spectrum of muon pairs observed in 400-GeV proton-nucleus collisions at Fermilab, near Chicago. The enhancement due to these resonances stands out against the rapidly falling continuum background. (aus Ref. [8])



L. Ledermann *et al.*,  
Fermilab (1977)