5. Einführung in die Teilchenphysik

5.1 Neue Teilchen und Antiteilchen

5.2 Additive Quantenzahlen zur Charakterisierung von Teilchen

5.3 Teilchen-Antiteilchen Reaktionen

5.4 Leptonen

5.5 Das Quark-Modell

5.6 Entdeckung der schweren Quarks (c,b und t)

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
$Q = -1e$, $m_e = 511$ keV/c^2 , Spin = ½ ħ, stabil, $\tau = \infty$
Das leichteste elektrisch geladene Teilchen

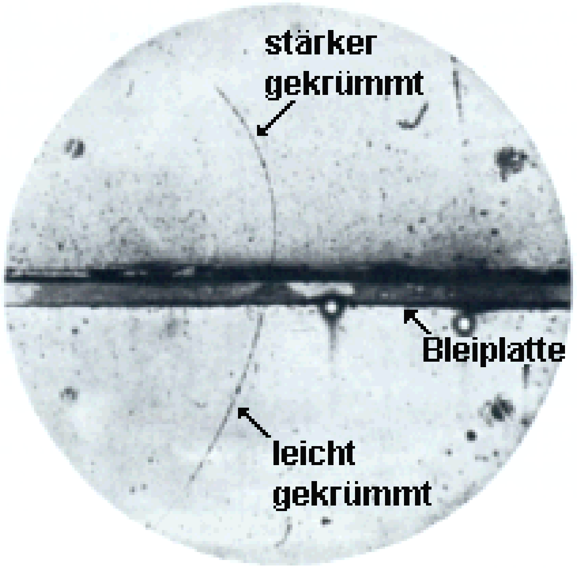
1911 - 1919: Rutherfordsche Streuexperimente,
Identifizierung des Wasserstoffkerns als Proton

1930: Neutrino-Hypothese von Pauli

1932: Entdeckung des Neutrons durch J. Chadwick

Wechselwirkungen: Gravitation, elektromagnetische Wechselwirkung,
starke Wechselwirkung (Kernkräfte),
und schwache Wechselwirkung (β-Zerfall)

5.1.2. Antimaterie



1932: Anderson entdeckt das **Positron**

(systematische Durchmusterung von Nebelkammer-aufnahmen von Teilchenspuren, die durch Höhenstrahlung erzeugt wurden, pos. geladen, große Reichweite, ≠ Proton)

$Q = +1e$, $m_e = 511$ keV/c^2 , Spin = ½ ħ,
stabil (im Vakuum), $\tau = \infty$

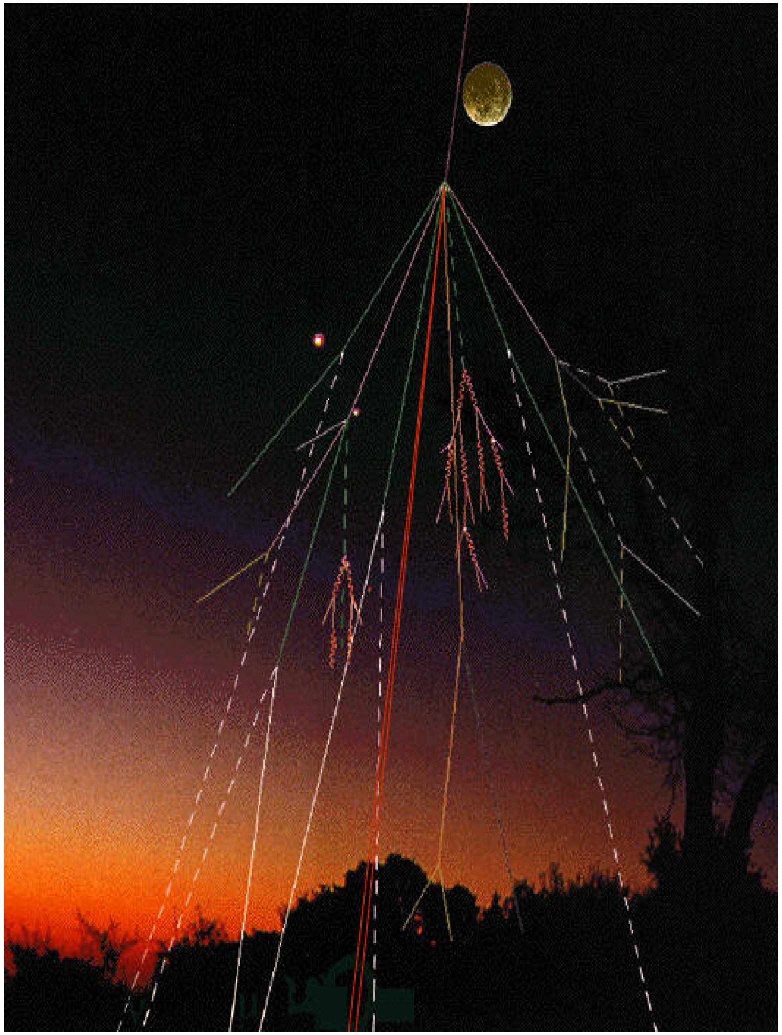
- Wurde zunächst als positiv geladenes Elektron interpretiert.

- **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:

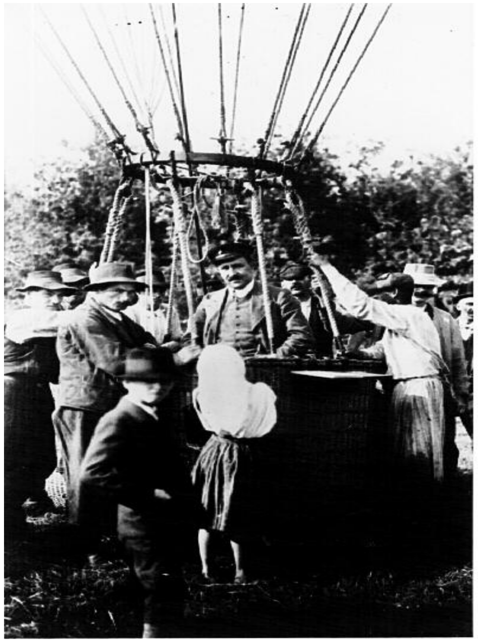
zu jedem Teilchen muss es ein Antiteilchen geben, das dieselbe Masse hat, aber entgegengesetzte additive Quantenzahlen
(Symmetrie zwischen Materie und Antimaterie)

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

$m_X = 105$ MeV / c^2

Ursprüngliche Assoziation als „Yukawa-Teilchen“ π - 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 $\frac{1}{2}\hbar$, $m = 105{,}7$ MeV/c^2)

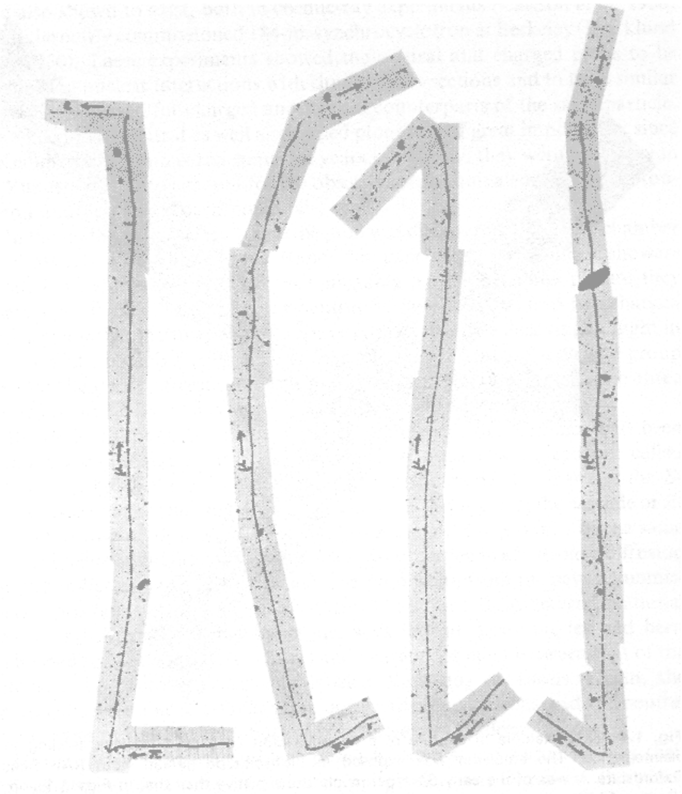
Wozu ?? „who ordered that ??“

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: $\tau_\mu = 2{,}20 \cdot 10^{-6}$ sec
$c\,\tau_\mu = 659{,}1$ m

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

Experiment: Photographische Emulsion
auf Berghöhe



heutige Bezeichnung: π – Meson

m_π = 139,6 MeV/c^2

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

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

Rom: Meereshöhe → fast nur noch Myonen

Zerfälle:

$$\pi^\pm \longrightarrow \mu^\pm + \nu_\mu$$

$$\mu^\pm \longrightarrow e^\pm + \nu_e + \nu_\mu$$

5.1.4. Weitere, sog. *Seltsame Teilchen*

s. Vorlesung

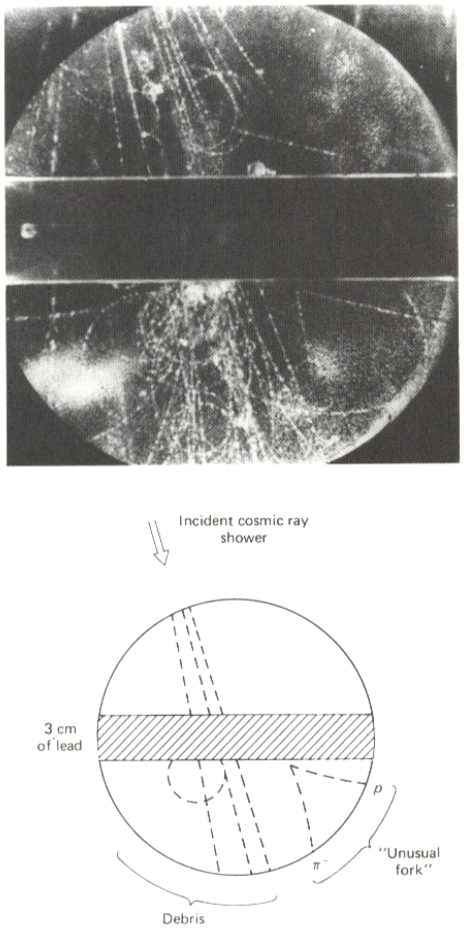
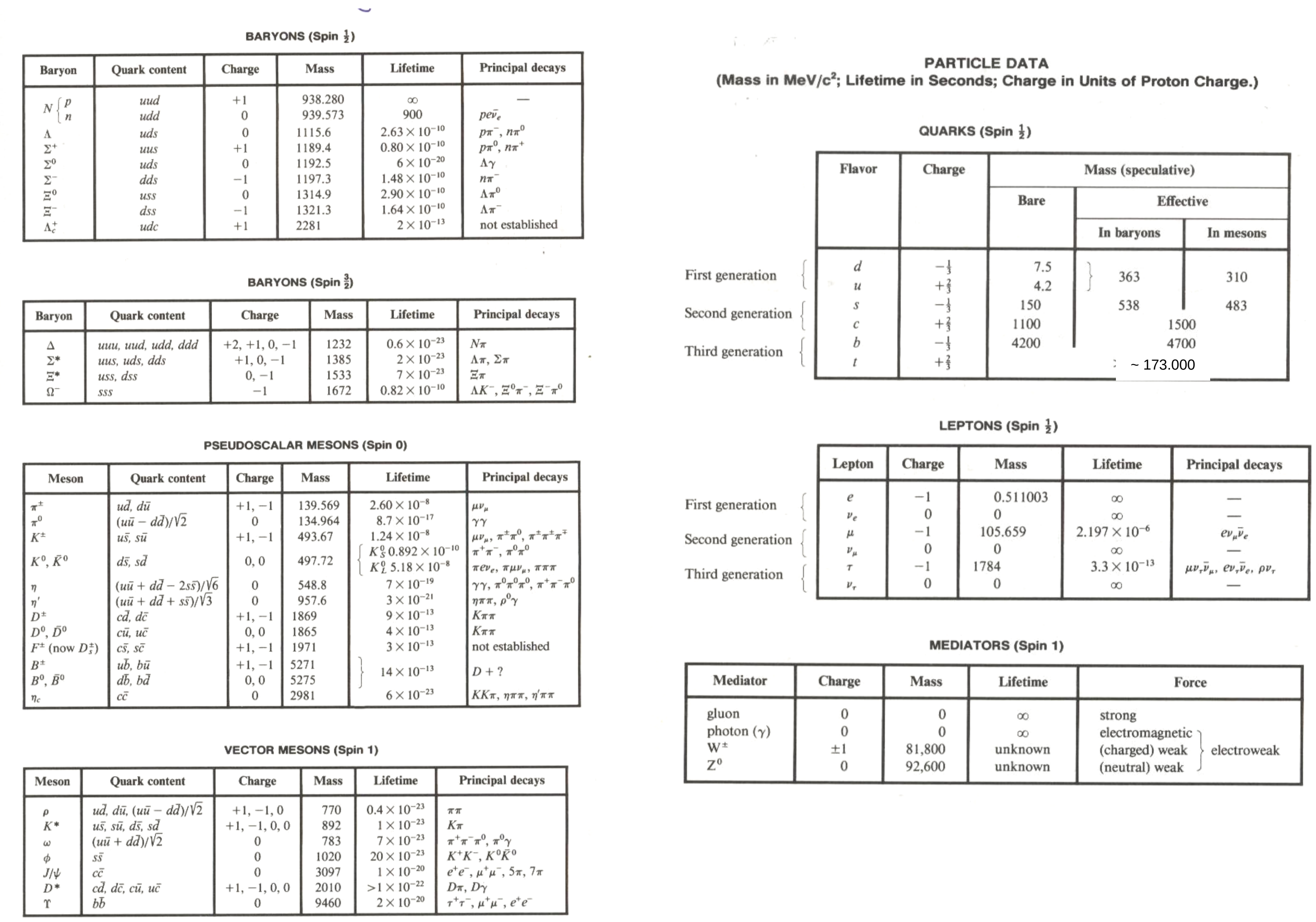


Figure 1.8 The first strange particle. Cosmic rays strike a lead plate, producing a K^0, which subsequently decays into a pair of charged pions. (Photo courtesy of Prof. G. D. Rochester. Reprinted by permission from *Nature* **160,** 855. Copyright © 1947, Macmillan Journals Limited.)



BARYONS (Spin $\frac{1}{2}$)

Baryon	Quark content	Charge	Mass	Lifetime	Principal decays
$N\ p$	uud	+1	938.280	∞	—
$N\ n$	udd	0	939.573	900	$pe\bar{\nu}_e$
Λ	uds	0	1115.6	2.63×10^{-10}	$p\pi^-, n\pi^0$
Σ^+	uus	+1	1189.4	0.80×10^{-10}	$p\pi^0, n\pi^+$
Σ^0	uds	0	1192.5	6×10^{-20}	$\Lambda\gamma$
Σ^-	dds	−1	1197.3	1.48×10^{-10}	$n\pi^-$
Ξ^0	uss	0	1314.9	2.90×10^{-10}	$\Lambda\pi^0$
Ξ^-	dss	−1	1321.3	1.64×10^{-10}	$\Lambda\pi^-$
Λ_c^+	udc	+1	2281	2×10^{-13}	not established

BARYONS (Spin $\frac{3}{2}$)

Baryon	Quark content	Charge	Mass	Lifetime	Principal decays
Δ	uuu, uud, udd, ddd	+2, +1, 0, −1	1232	0.6×10^{-23}	$N\pi$
Σ^*	uus, uds, dds	+1, 0, −1	1385	2×10^{-23}	$\Lambda\pi, \Sigma\pi$
Ξ^*	uss, dss	0, −1	1533	7×10^{-23}	$\Xi\pi$
Ω^-	sss	−1	1672	0.82×10^{-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	2.60×10^{-8}	$\mu\nu_\mu$
π^0	$(u\bar{u} - d\bar{d})/\sqrt{2}$	0	134.964	8.7×10^{-17}	$\gamma\gamma$
$K^\pm$	$u\bar{s}, s\bar{u}$	+1, −1	493.67	1.24×10^{-8}	$\mu\nu_\mu, \pi^\pm\pi^0, \pi^\pm\pi^\pm\pi^\mp$
$K^0, \bar{K}^0$	$d\bar{s}, s\bar{d}$	0, 0	497.72	$K^0_S\ 0.892 \times 10^{-10}$ $K^0_L\ 5.18 \times 10^{-8}$	$\pi^+\pi^-, \pi^0\pi^0$ $\pi e\nu_e, \pi\mu\nu_\mu, \pi\pi\pi$
η	$(u\bar{u} + d\bar{d} - 2s\bar{s})/\sqrt{6}$	0	548.8	7×10^{-19}	$\gamma\gamma, \pi^0\pi^0\pi^0, \pi^+\pi^-\pi^0$
η'	$(u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$	0	957.6	3×10^{-21}	$\eta\pi\pi, \rho^0\gamma$
$D^\pm$	$c\bar{d}, d\bar{c}$	+1, −1	1869	9×10^{-13}	$K\pi\pi$
$D^0, \bar{D}^0$	$c\bar{u}, u\bar{c}$	0, 0	1865	4×10^{-13}	$K\pi\pi$
$F^\pm$ (now $D_s^\pm$)	$c\bar{s}, s\bar{c}$	+1, −1	1971	3×10^{-13}	not established
$B^\pm$	$u\bar{b}, b\bar{u}$	+1, −1	5271	14×10^{-13}	$D + ?$
$B^0, \bar{B}^0$	$d\bar{b}, b\bar{d}$	0, 0	5275		
η_c	$c\bar{c}$	0	2981	6×10^{-23}	$KK\pi, \eta\pi\pi, \eta'\pi\pi$

VECTOR MESONS (Spin 1)

Meson	Quark content	Charge	Mass	Lifetime	Principal decays
ρ	$u\bar{d}, d\bar{u}, (u\bar{u} - d\bar{d})/\sqrt{2}$	+1, −1, 0	770	0.4×10^{-23}	$\pi\pi$
K^*	$u\bar{s}, s\bar{u}, d\bar{s}, s\bar{d}$	+1, −1, 0, 0	892	1×10^{-23}	$K\pi$
ω	$(u\bar{u} + d\bar{d})/\sqrt{2}$	0	783	7×10^{-23}	$\pi^+\pi^-\pi^0, \pi^0\gamma$
ϕ	$s\bar{s}$	0	1020	20×10^{-23}	$K^+K^-, K^0\bar{K}^0$
J/ψ	$c\bar{c}$	0	3097	1×10^{-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	$>1 \times 10^{-22}$	$D\pi, D\gamma$
Υ	$b\bar{b}$	0	9460	2×10^{-20}	$\tau^+\tau^-, \mu^+\mu^-, e^+e^-$

PARTICLE DATA
(Mass in MeV/c^2; Lifetime in Seconds; Charge in Units of Proton Charge.)

QUARKS (Spin $\frac{1}{2}$)

	Flavor	Charge	Mass (speculative)		
			Bare	Effective	
				In baryons	In mesons
First generation	d	$-\frac{1}{3}$	7.5	363	310
	u	$+\frac{2}{3}$	4.2		
Second generation	s	$-\frac{1}{3}$	150	538	483
	c	$+\frac{2}{3}$	1100	1500	
Third generation	b	$-\frac{1}{3}$	4200	4700	
	t	$+\frac{2}{3}$		~ 173.000	

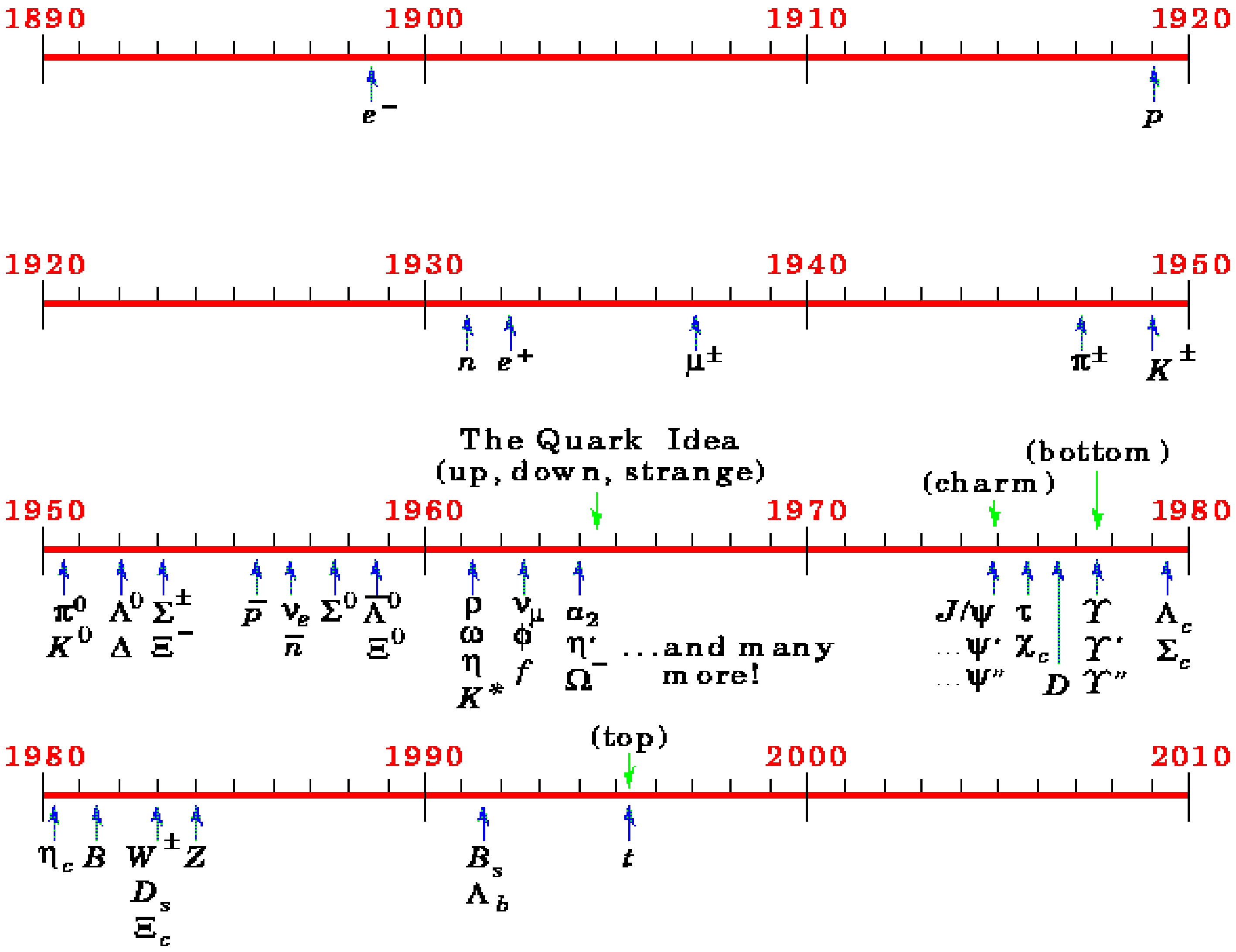
LEPTONS (Spin $\frac{1}{2}$)

	Lepton	Charge	Mass	Lifetime	Principal decays
First generation	e	−1	0.511003	∞	—
	ν_e	0	0	∞	—
Second generation	μ	−1	105.659	2.197×10^{-6}	$e\nu_\mu\bar{\nu}_e$
	ν_μ	0	0	∞	—
Third generation	τ	−1	1784	3.3×10^{-13}	$\mu\nu_\tau\bar{\nu}_\mu, e\nu_\tau\bar{\nu}_e, \rho\nu_\tau$
	ν_τ	0	0	∞	—

MEDIATORS (Spin 1)

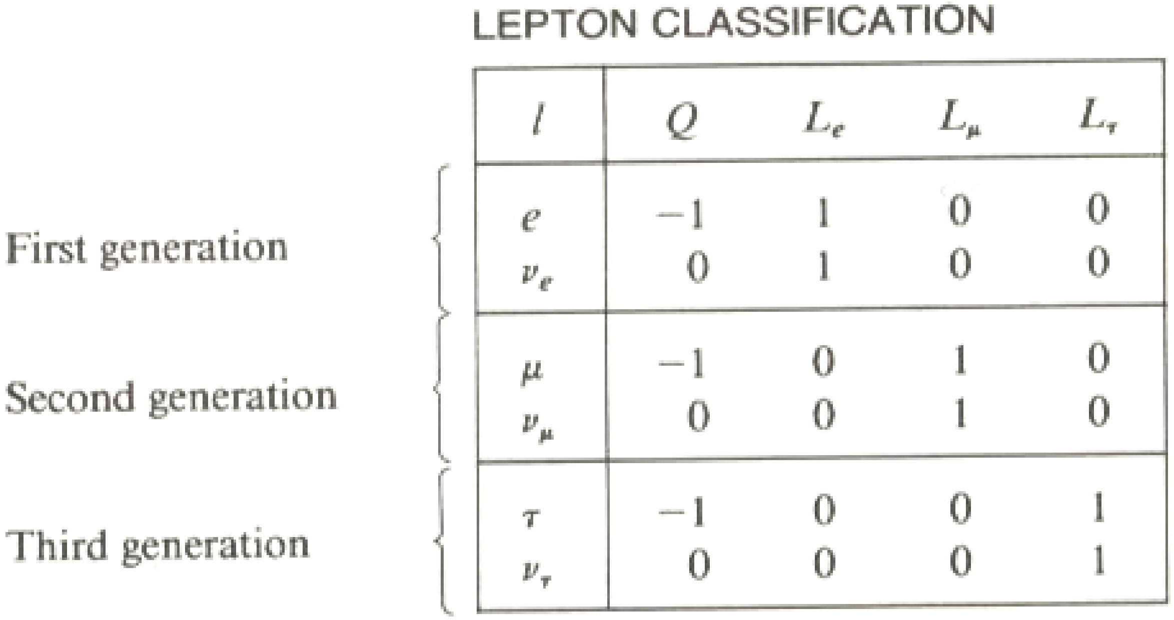
Mediator	Charge	Mass	Lifetime	Force	
gluon	0	0	∞	strong	
photon (γ)	0	0	∞	electromagnetic	electroweak
$W^\pm$	±1	81,800	unknown	(charged) weak	
Z^0	0	92,600	unknown	(neutral) weak	

5.1.5. Entdeckte Teilchen



5.2 Additive Quantenzahlen

zur Charakterisierung von Teilchen



LEPTON CLASSIFICATION

	l	Q	L_e	L_μ	L_τ
First generation	e	-1	1	0	0
	ν_e	0	1	0	0
Second generation	μ	-1	0	1	0
	ν_μ	0	0	1	0
Third generation	τ	-1	0	0	1
	ν_τ	0	0	0	1

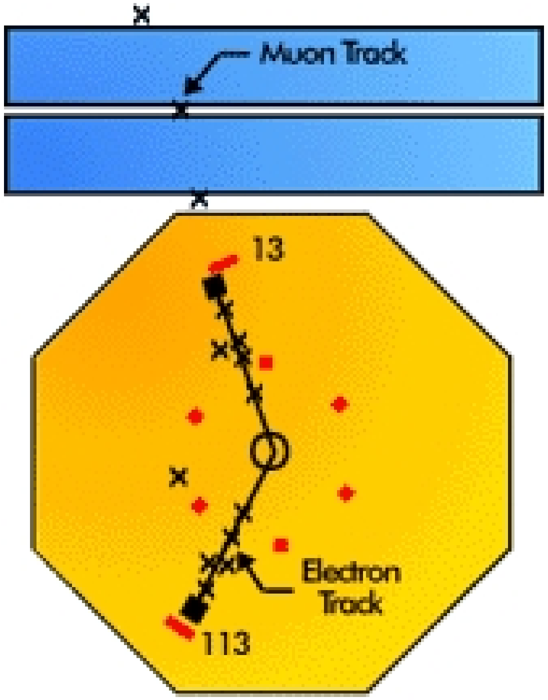
5.3 Teilchen–Antiteilchen Reaktionen

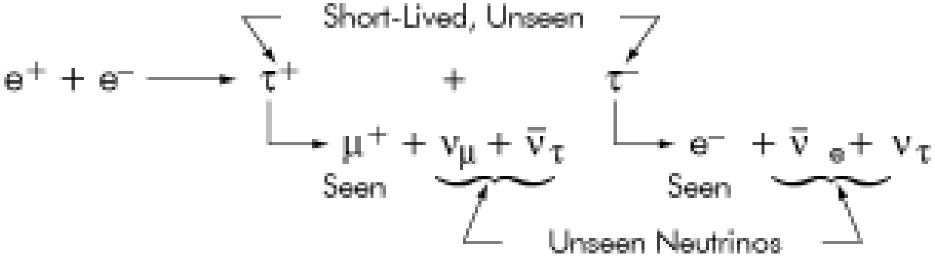
5.4 Leptonen

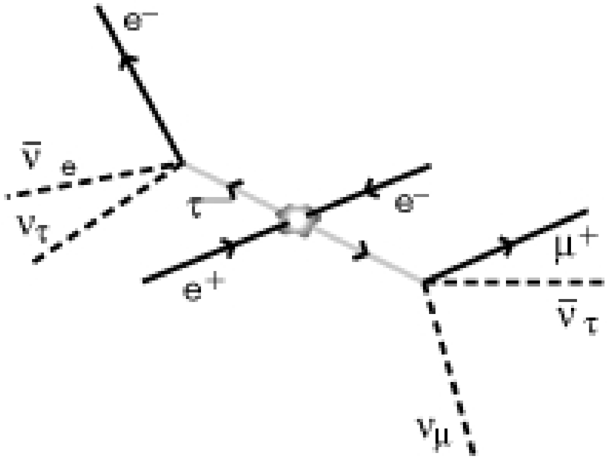
Die Entdeckung des τ–Leptons

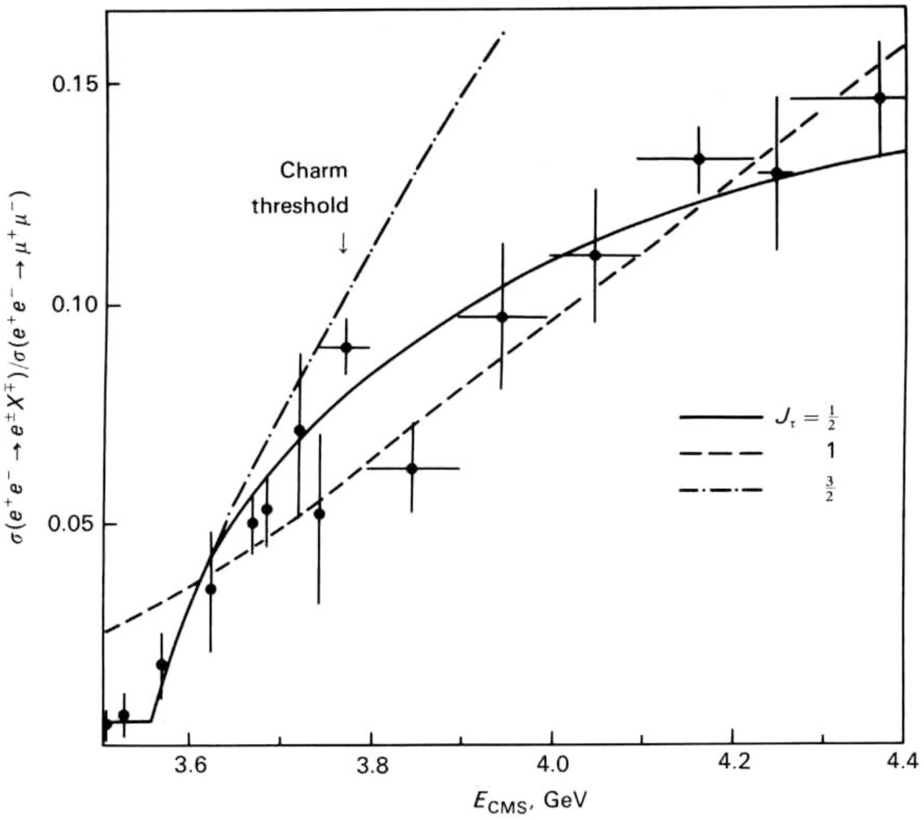
1975: Stanford Linear Accelerator Center, SLAC, M. Perl
Studium von e^+e^- Kollisionen mit dem MARK-I Detektor am
Speicherring SPEAR (Strahlenergie 4 GeV)

Entdeckung eines neuen, schweren Leptons
Tau-Lepton,   m(τ) = 1.78 GeV/c²









Analysis of τ-lepton production by DELCO collaboration at SLAC e^+e^- collider SPEAR (Bacino *et al.* 1978). Pair production of τ-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 τ.

(aus Ref. [8])

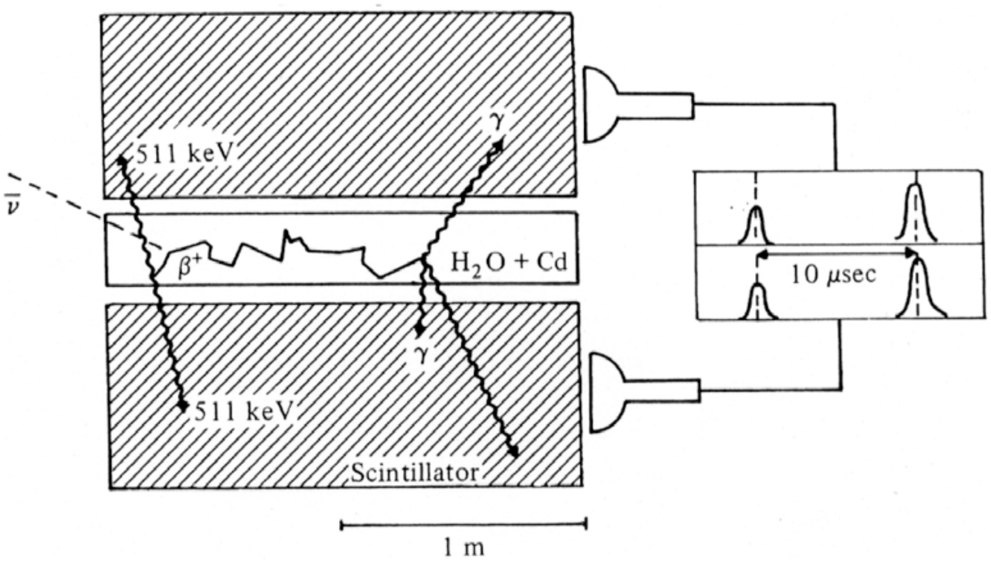
Experimenteller Nachweis des Neutrinos

1956: C.L. Cowan und F. Reines,
Neutrinoquelle: Kernreaktor (Savannah River, South Carolina, USA)
Nachweisreaktion: Inverser β-Zerfall **$\bar{\nu}_e + p \rightarrow n + e^+$**

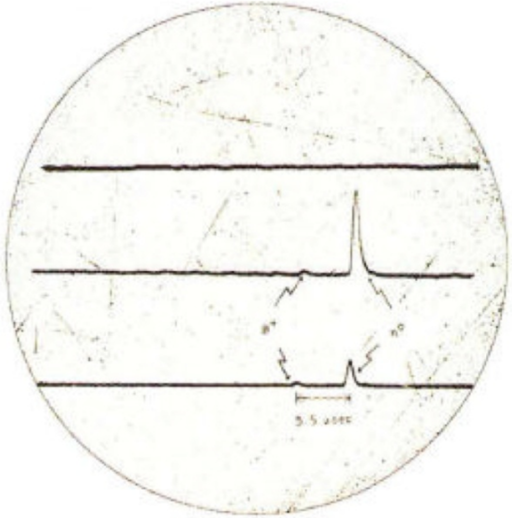
Abstand zum Detektor: 11 m, Neutrinofluss: $5 \cdot 10^{13}$ cm^{-2} sec^{-1}

Detektor: Flüssigszintillator mit Photomultiplier

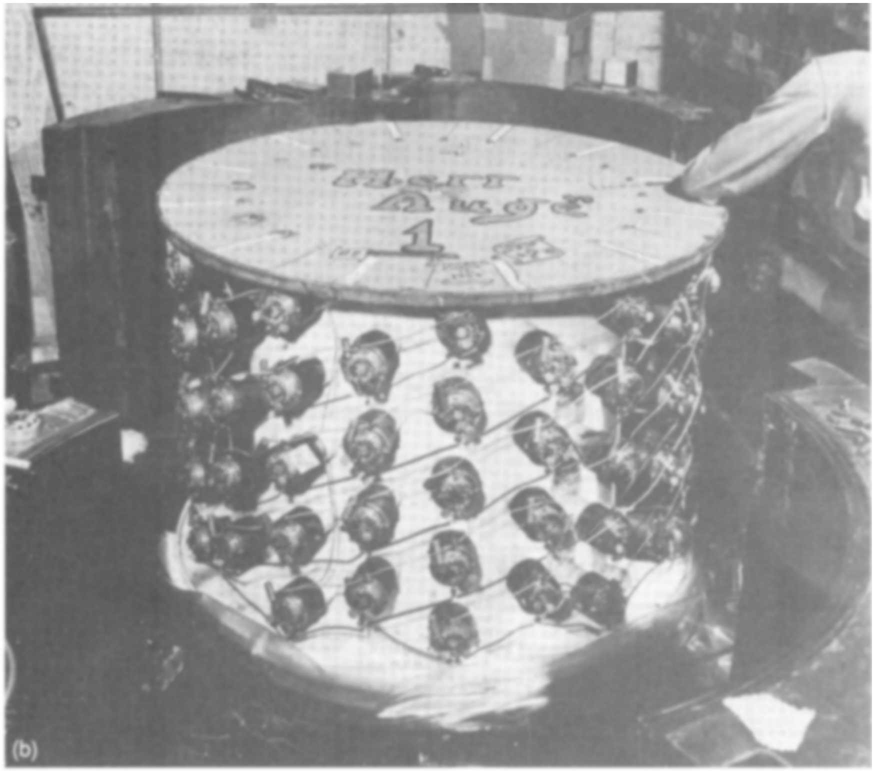
- Promptes Signal: $e^+ + e^- \rightarrow \gamma\gamma$
– Verzögertes Signal: $n + {}^{108}Cd \rightarrow {}^{109}Cd^* \rightarrow {}^{109}Cd + \gamma$



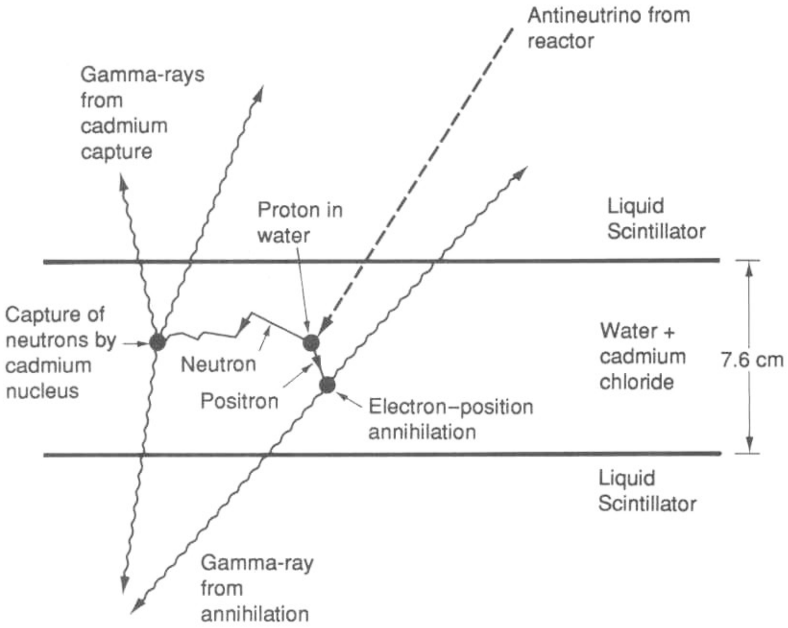
Das erste Neutrinosignal



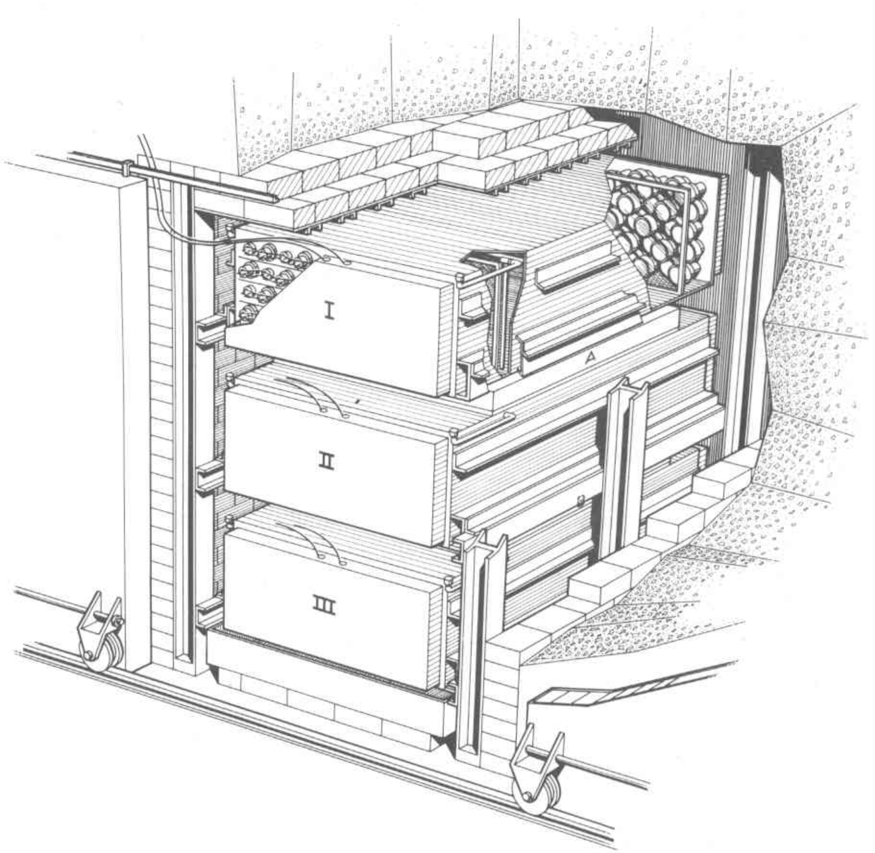
Clyde Cowan (far left) and Fred Raines (far right) with their team on 'Project Poltergeist', the prototype neutrino detector that demonstrated the potential of the technique they had chosen.



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)

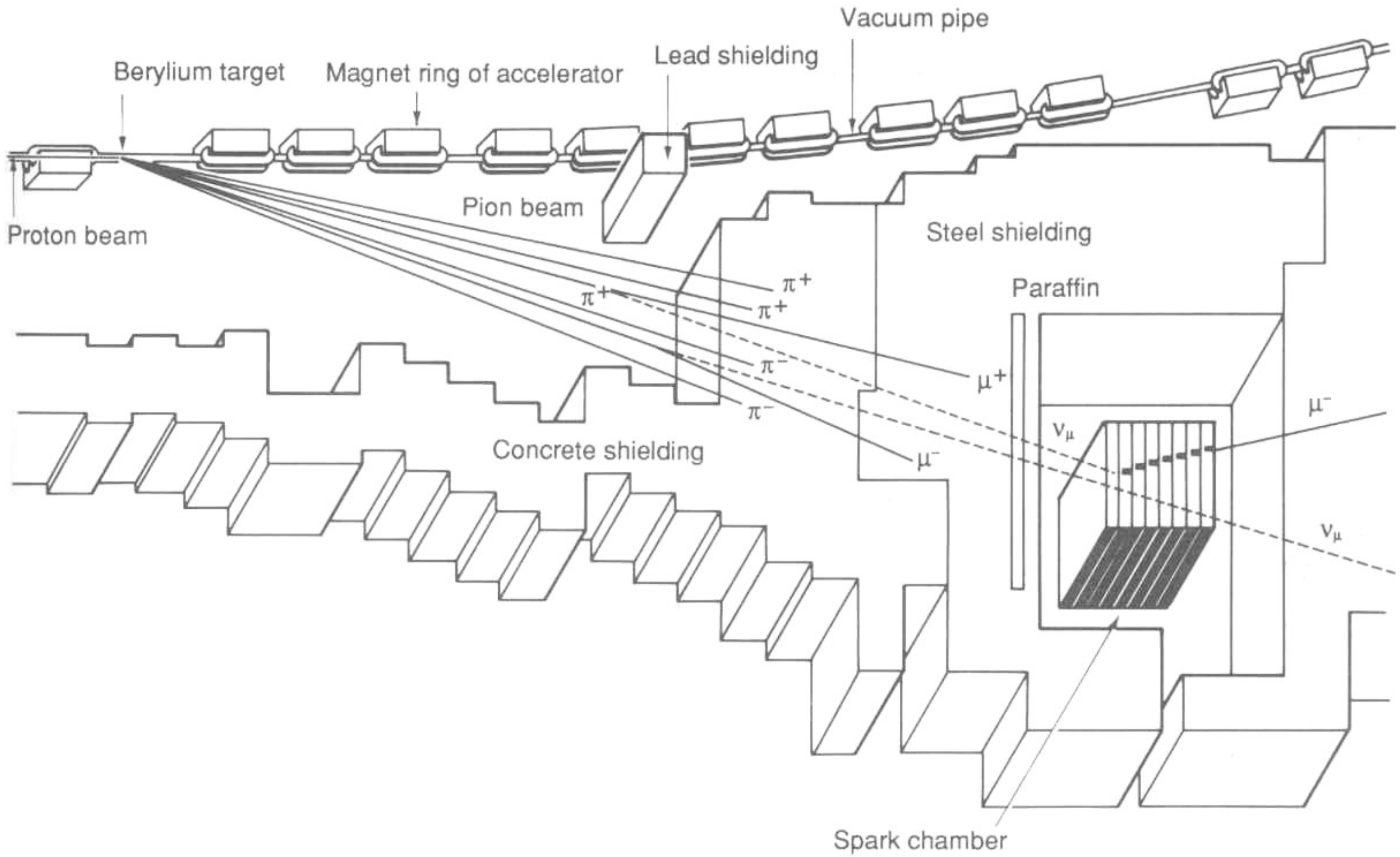


The method Reines and Cowan used finally to detect neutrinos was a three-step process: first a proton in the water would absorb a neutrino, and produce a neutron and a positron; then almost immediately the positron would annihilate with an electron, emitting two back-to-back gamma-rays which could be 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.



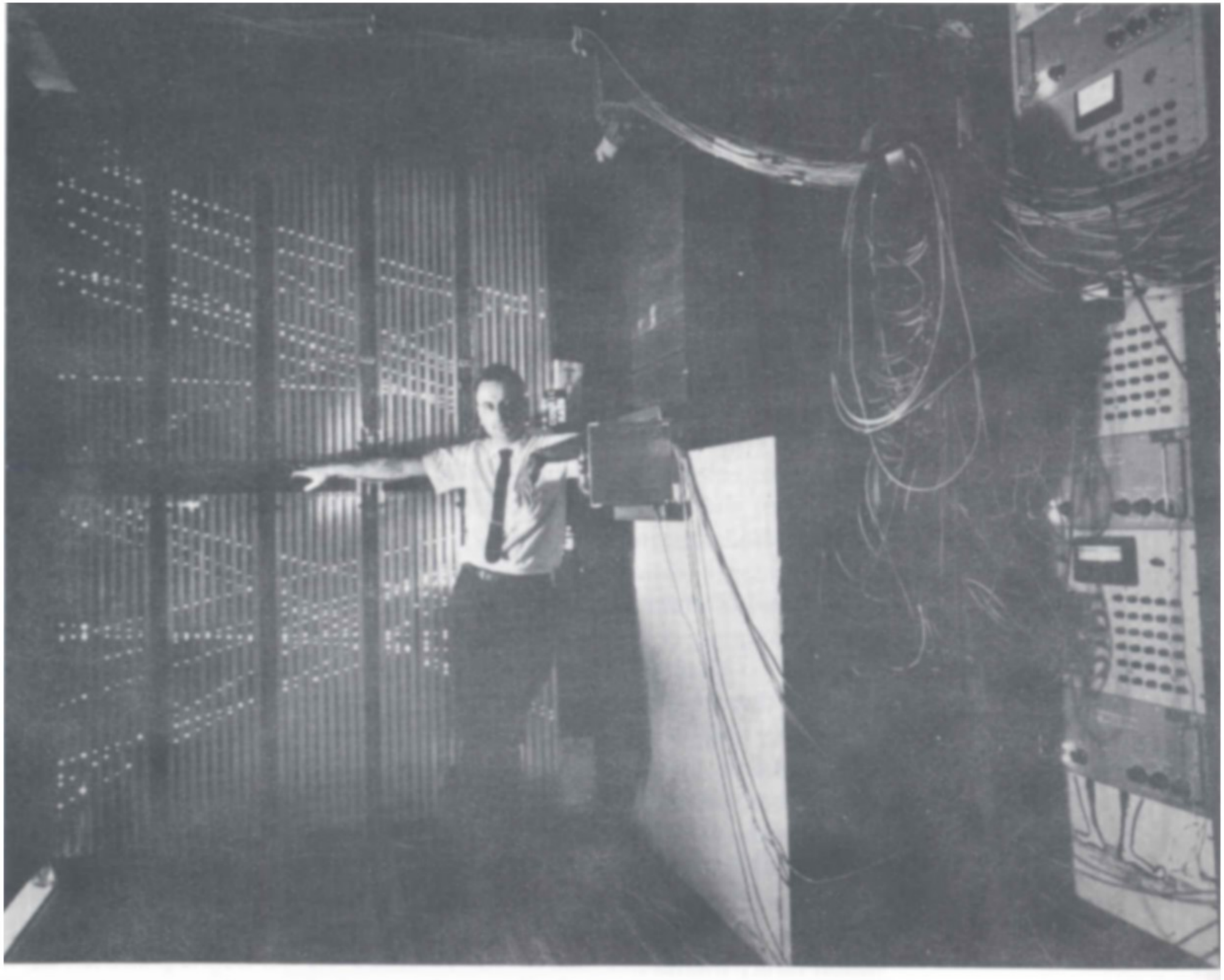
The final assembly of Cowan and Reines used to detect neutrinos from the powerful nuclear reactor at Savannah River, South Carolina. The large tanks labelled I, II and III contained liquid scintillator, and were each viewed by 110 phototubes; the smaller ones sandwiched between, labelled A and B, contained 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.

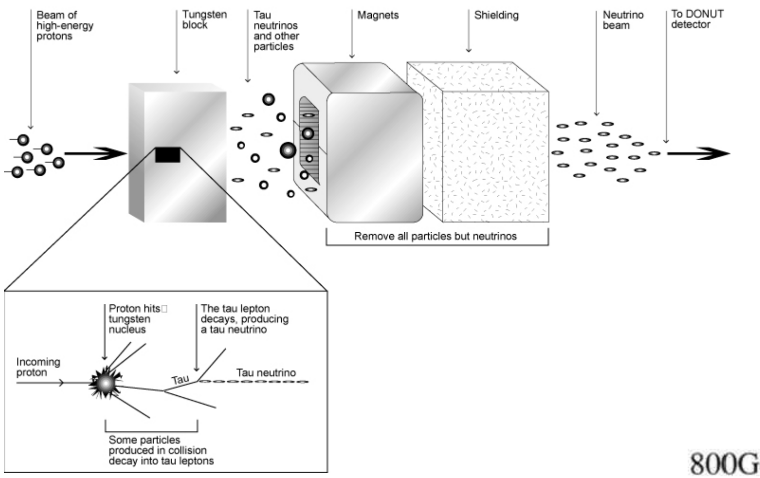
Steinberger (links),
Ledermann (2ter von rechts),
Schwartz (rechts) et al.

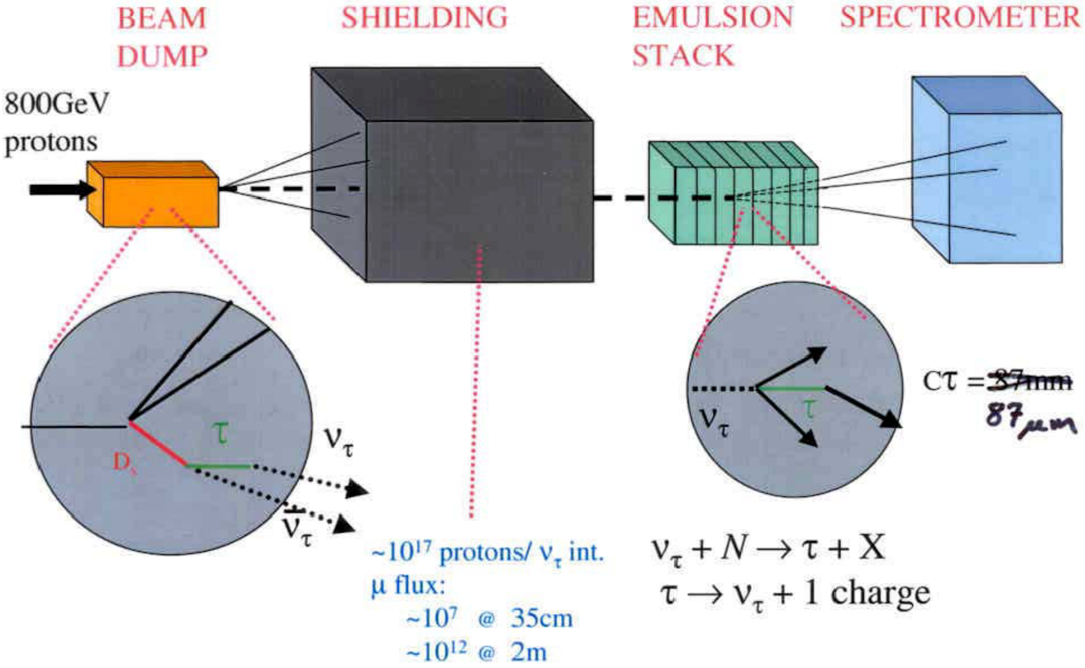


Mel Schwartz standing in front of the 10-tonne spark chamber used in the ‚two-neutrino experiment‘. Each of the ten modules contains 1 ton of aluminium in the form of nine plates which are 2.5 centimeters thick and separated by a gas-filled gap of 1 centimeter. High voltage across the plates causes the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

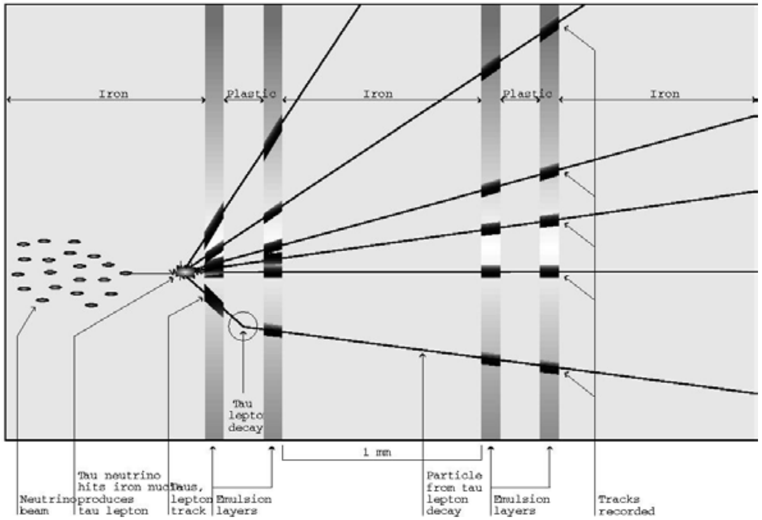
Experimenteller Nachweis des ν_τ (2000)

Creating a Tau Neutrino Beam

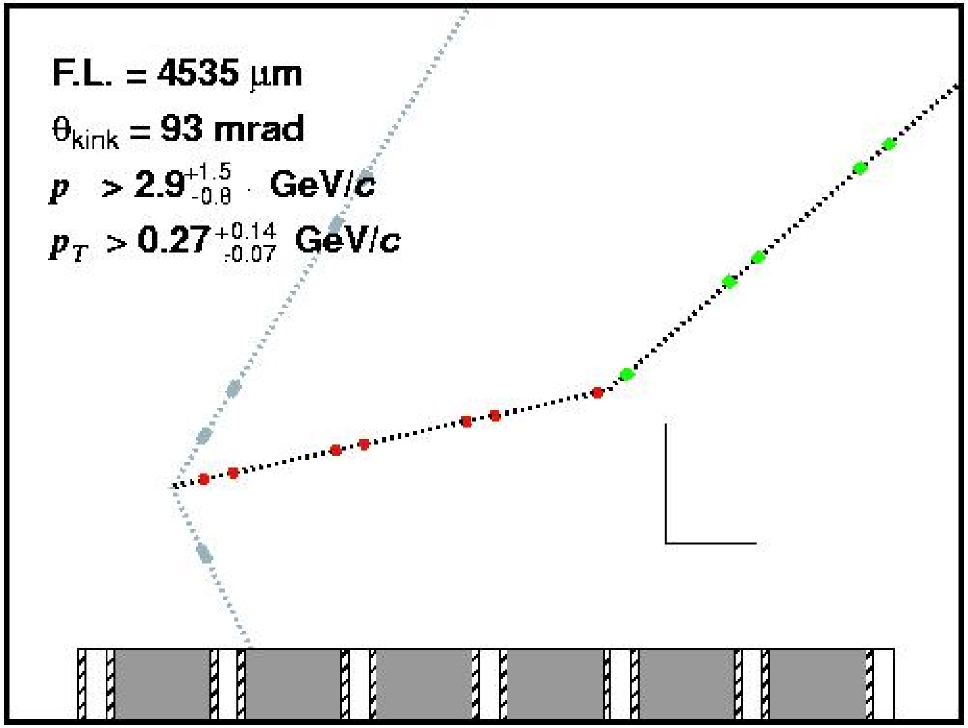




Experimenteller Nachweis des ν_τ (2000)



Prinzip des ν_τ Nachweises



Eins der vier registrierten Ereignisse
(DONUT-Kollaboration, Jul. 2000)

5.5 Das Quark-Modell

Können alle diese Teilchen elementar sein ??

1964: Quark-Hypothese

Gell-Mann

Zweig

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

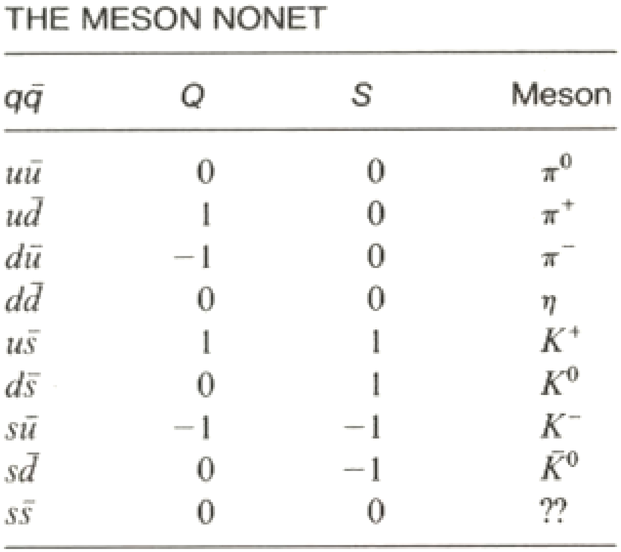
Hauptmotivation: Teilchenvielfalt ⇒ **neue Substruktur**

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

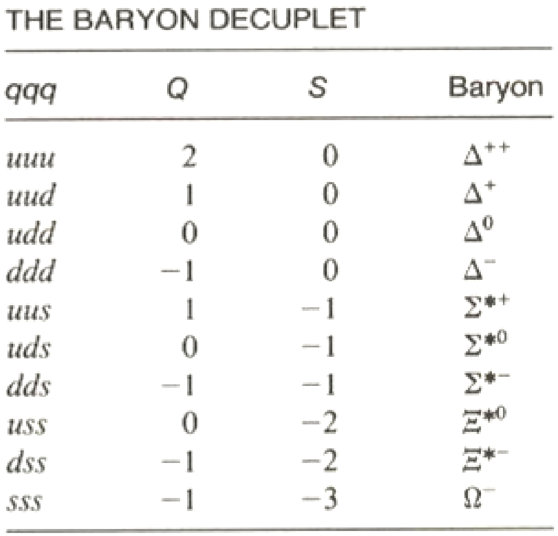
„- Three quarks for Muster Mark !
Sure he hasn´t got much of a bark
And sure any he has it´s all beside the mark.
But O Wreneagle Almighty wouldn´t un be a sky of a lark
To see that old buzzard about for uns shirt in the dark
And he hunting round for uns speckled trousers around by Palmerstown Park?“

aus Finnegans Wake, von James Joyce



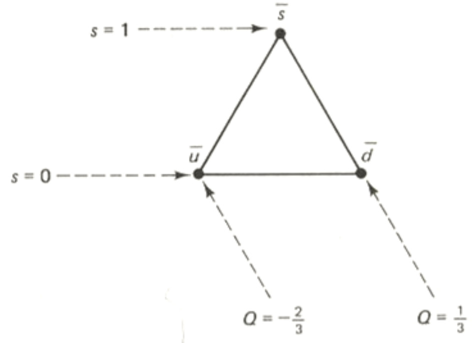
THE MESON NONET

$q\bar{q}$	Q	S	Meson
$u\bar{u}$	0	0	π^0
$u\bar{d}$	1	0	π^+
$d\bar{u}$	−1	0	π^-
$d\bar{d}$	0	0	η
$u\bar{s}$	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	??



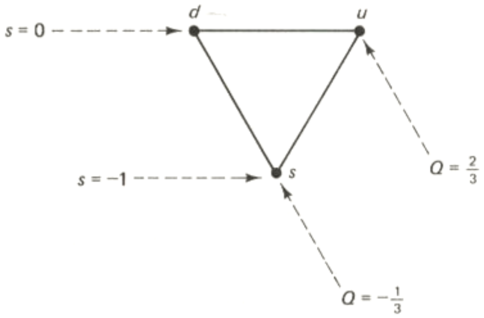
THE BARYON DECUPLET

qqq	Q	S	Baryon
uuu	2	0	Δ^{++}
uud	1	0	Δ^+
udd	0	0	Δ^0
ddd	−1	0	Δ^-
uus	1	−1	Σ^{*+}
uds	0	−1	Σ^{*0}
dds	−1	−1	Σ^{*-}
uss	0	−2	Ξ^{*0}
dss	−1	−2	Ξ^{*-}
sss	−1	−3	Ω^-

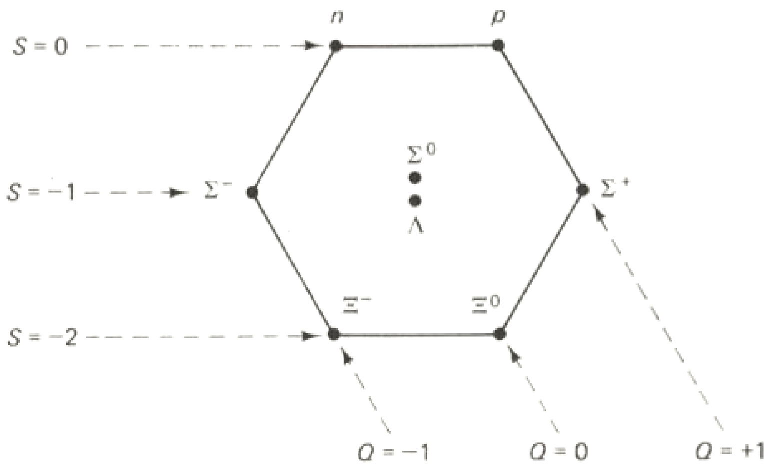


Die Bausteine:

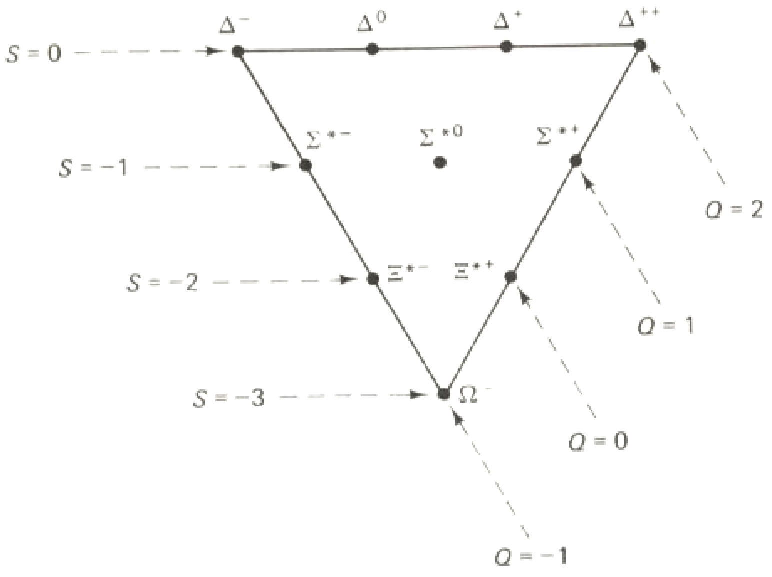
Quarks und Antiquarks



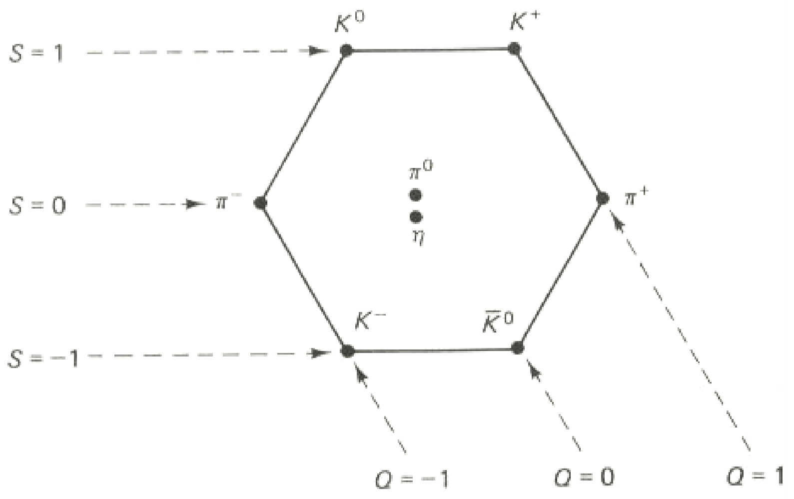
Das Quark-Modell



Das Baryonen-Oktett

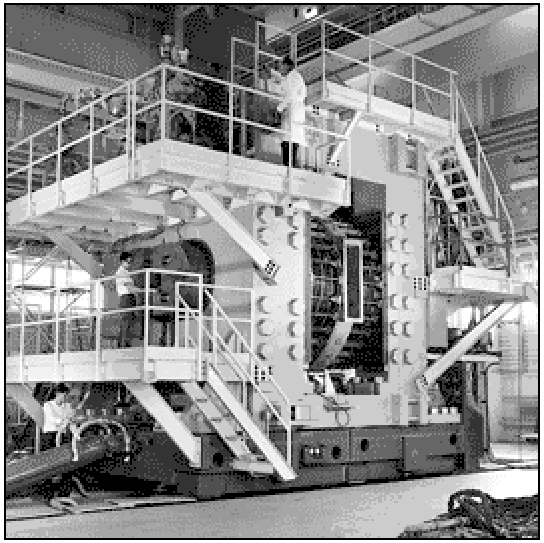


Das Baryonen-Dekuplett



Das Mesonen-Oktett

Die Entdeckung des Ω^-

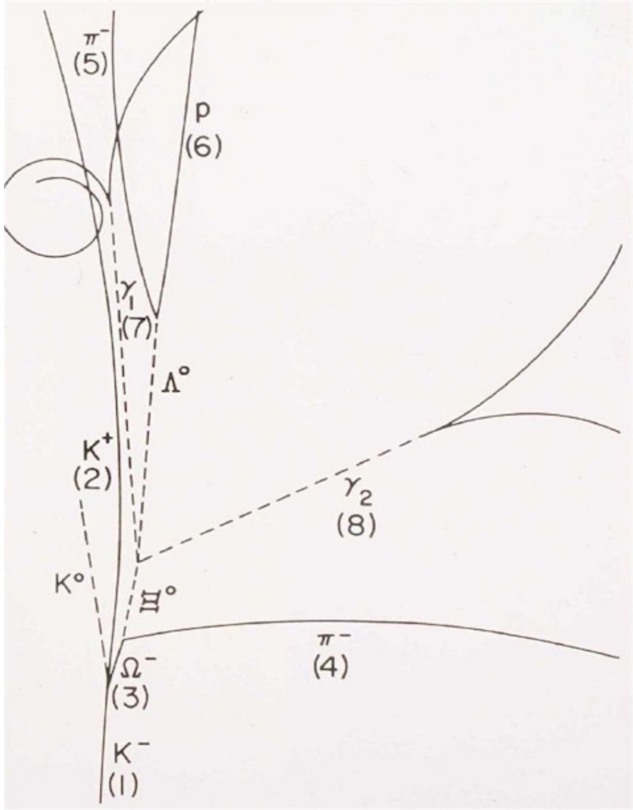


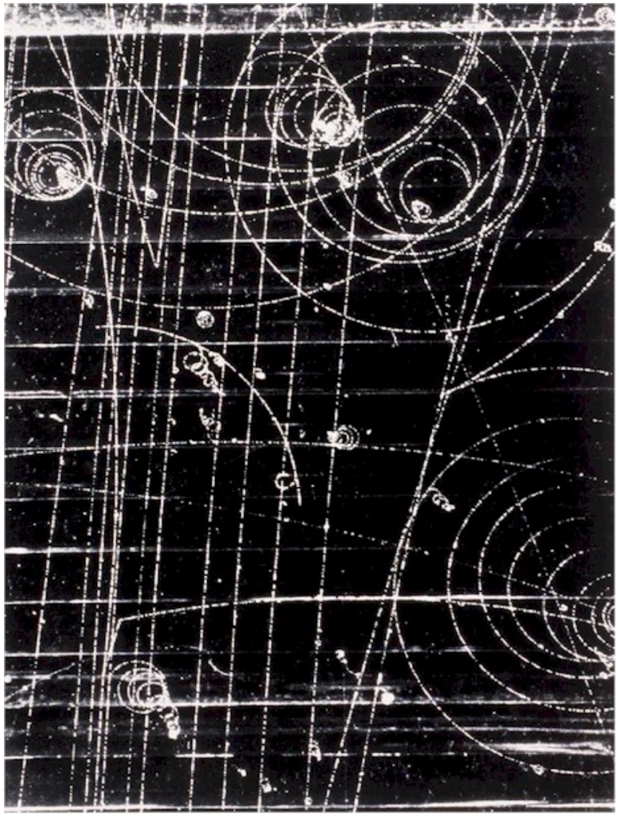
The 80-inch Bubble Chamber

1964: Brookhaven, AGS-Beschleuniger
80 Zoll Blasenkammer, flüssiger Wasserstoff

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

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





Experimentelle Evidenz für Quarks

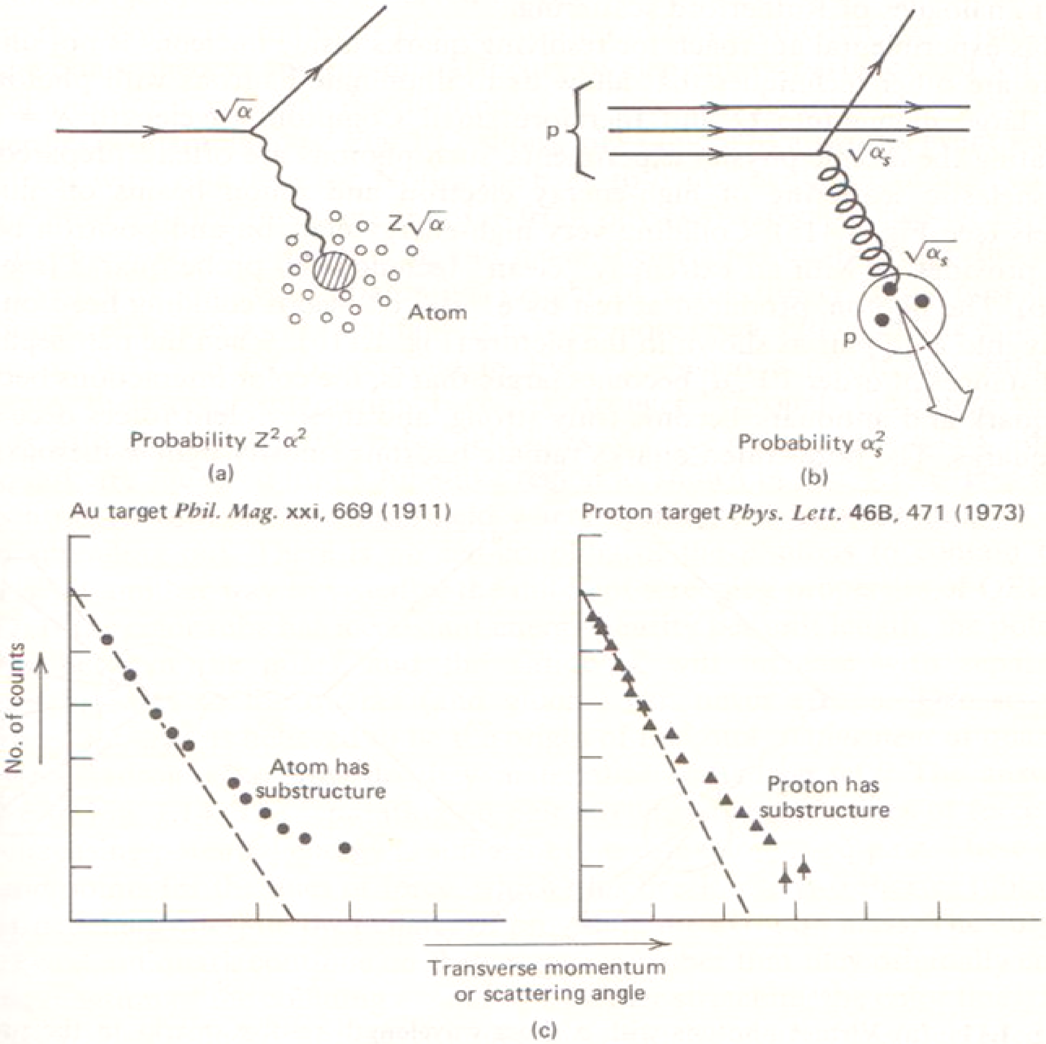
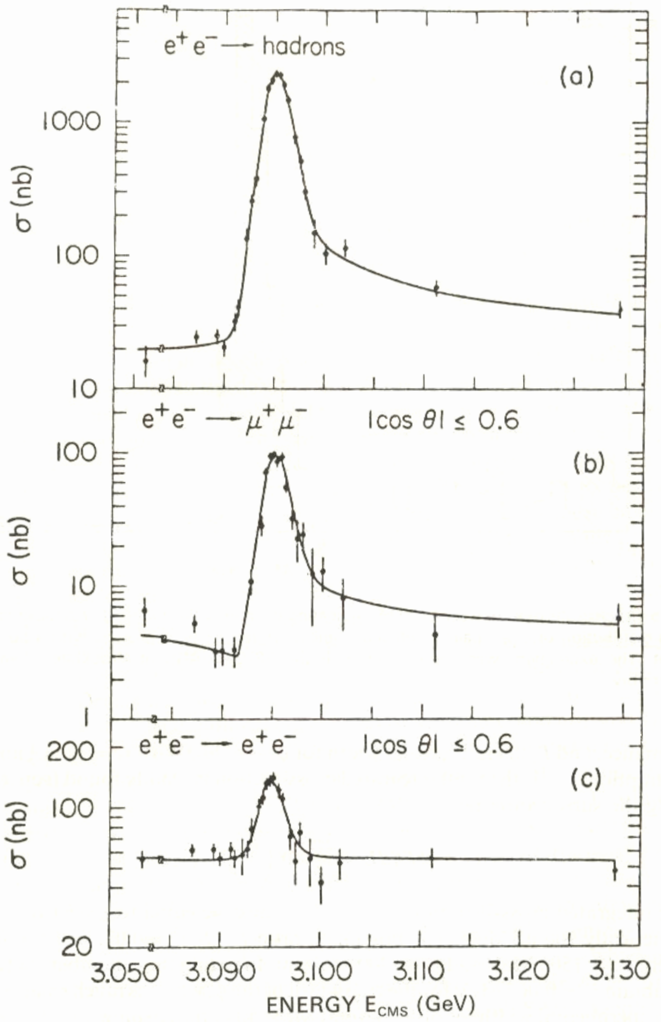


Fig. 1.10 (a) Inelastically scattered charged particle beam reveals the substructure of the atom. (b) Inelastically scattered proton beam reveals the quark structure of the proton target. (c) Experimental results. (aus Ref. [5])

5.6 Neue, schwere Quarks

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



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

(aus Ref. [8])

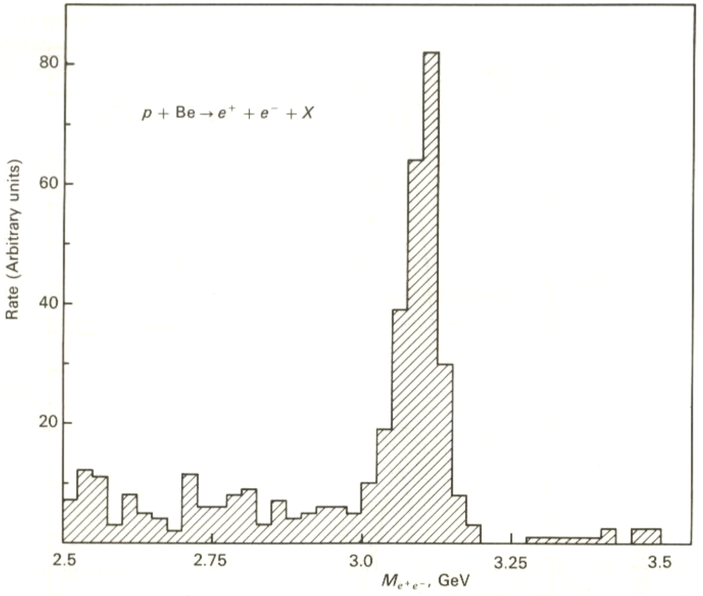
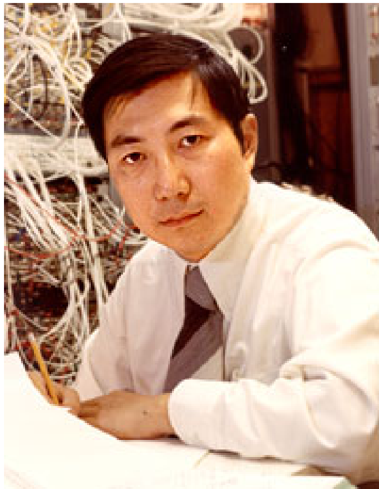


Fig. 5.11 Results of Aubert *et al.* (1974) indicating the narrow resonance ψ/J in the invariant-mass distribution of e^+e^- pairs produced in inclusive reactions of protons with a beryllium target. The experiment was carried out with the 28-GeV AGS at Brookhaven National Laboratory.

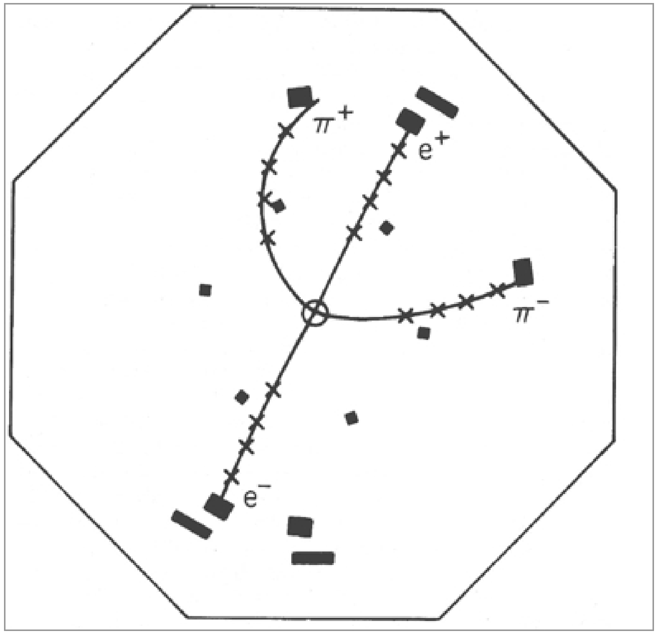
(aus Ref. [8])



Samuel S. Ting (1974)

Beobachteter Zerfall $\psi' \rightarrow J/\psi\, \pi^+\pi^- \rightarrow e^+e^-\, \pi^+\pi^-$

(aus Ref. [8])



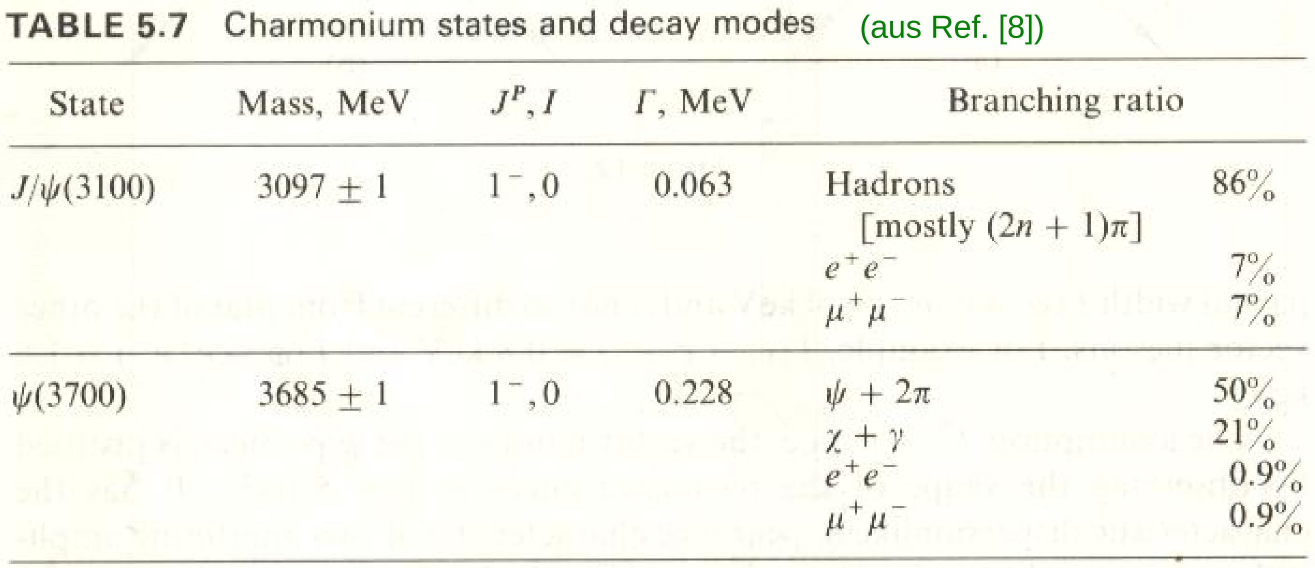


TABLE 5.7 Charmonium states and decay modes

(aus Ref. [8])

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

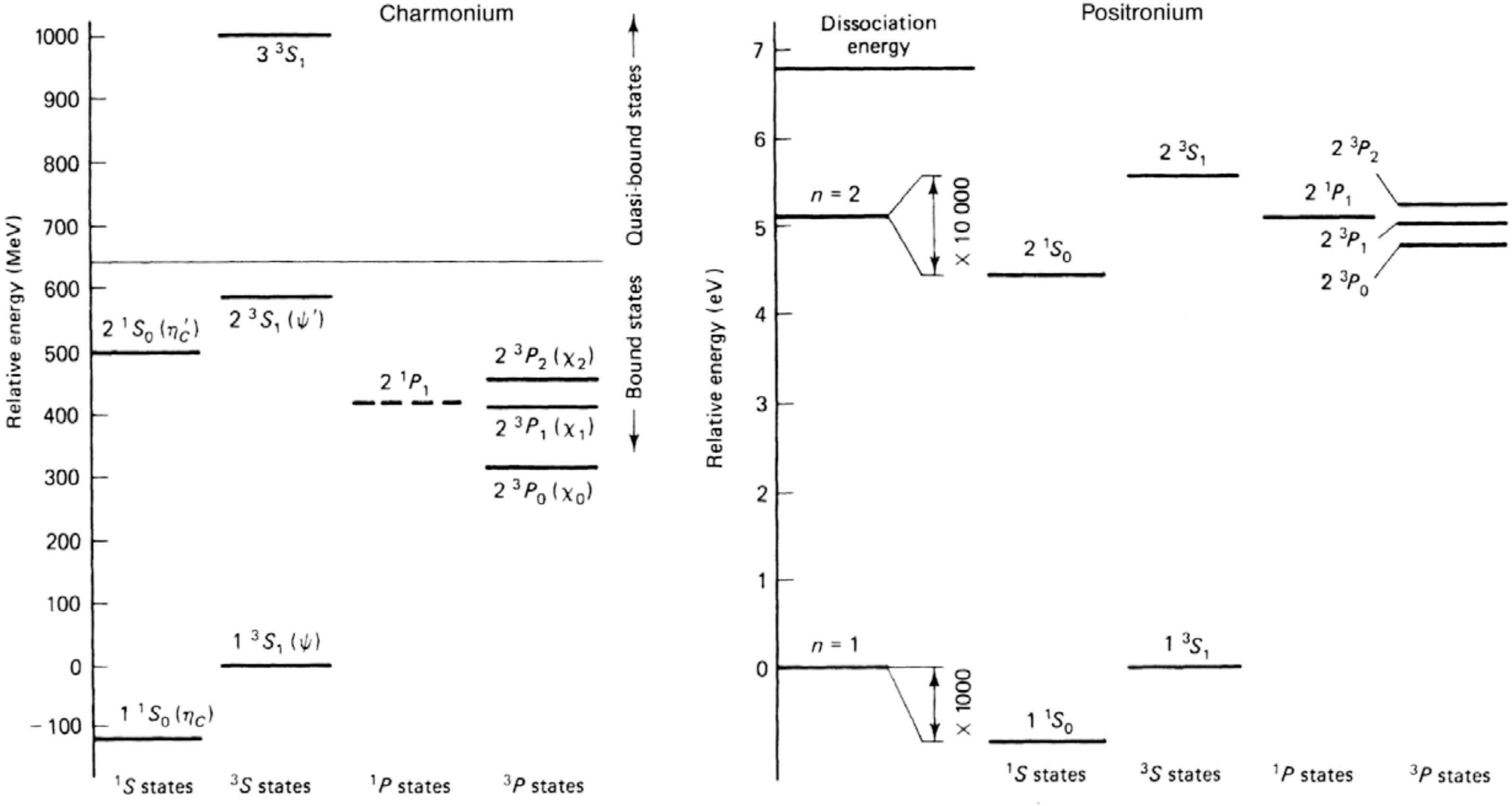


Fig. 5.6 Spectrum of energy levels in positronium and charmonium. Note that the scale is greater by a factor of 100 million for charmonium. In positronium, the various combinations of angular momentum cause only minuscule shifts in energy (shown by expanding the vertical scale), but in charmonium the shifts are much larger. All energies are given with reference to the 1^3S_1 state. At 6.8 eV positronium dissociates. At 633 MeV above the energy of the ψ charmonium becomes quasi-bound, because it can decay into D^0 and $\overline{D}^0$ mesons. (*Source*: Bloom, E. and Feldman, G. (May 1982) 'Quarkonium', *Scientific American*, p. 66, reprinted by permission.)

Entdeckung der bb-Resonanzen (Y) (1977)

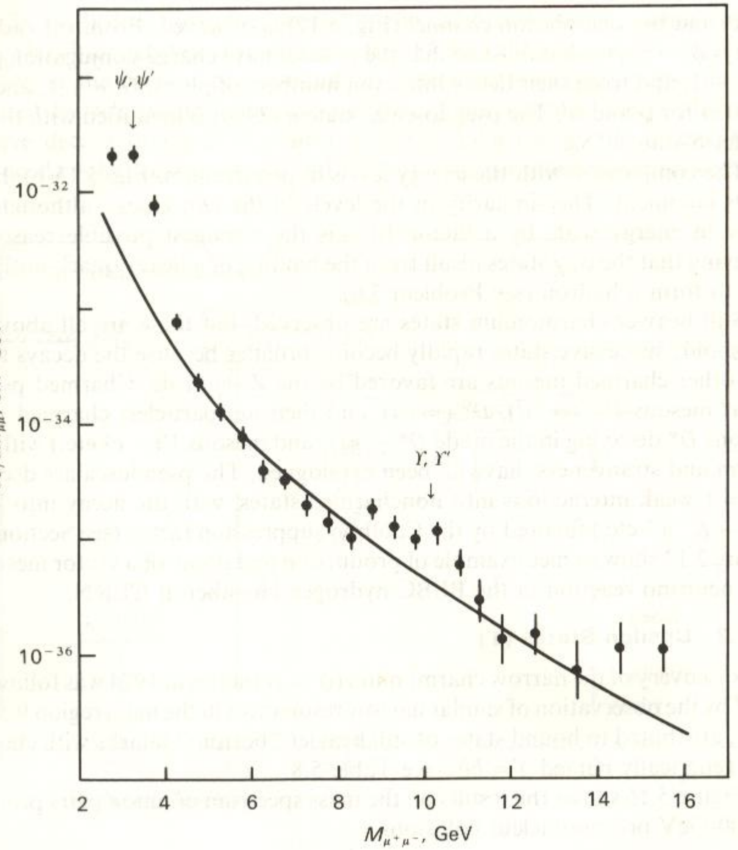


Fig. 5.16 First evidence for the upsilon resonances Υ, Υ', obtained by Herb *et al.* (1977) from the spectrum of muon pairs observed in 400-GeV proton-nucleus collisions at Fermilab, near Chicago. The enhancement due to these resonances stands out against the rapidly falling continuum background.

(aus Ref. [8])

L. Ledermann et al.,
Fermilab (1977)