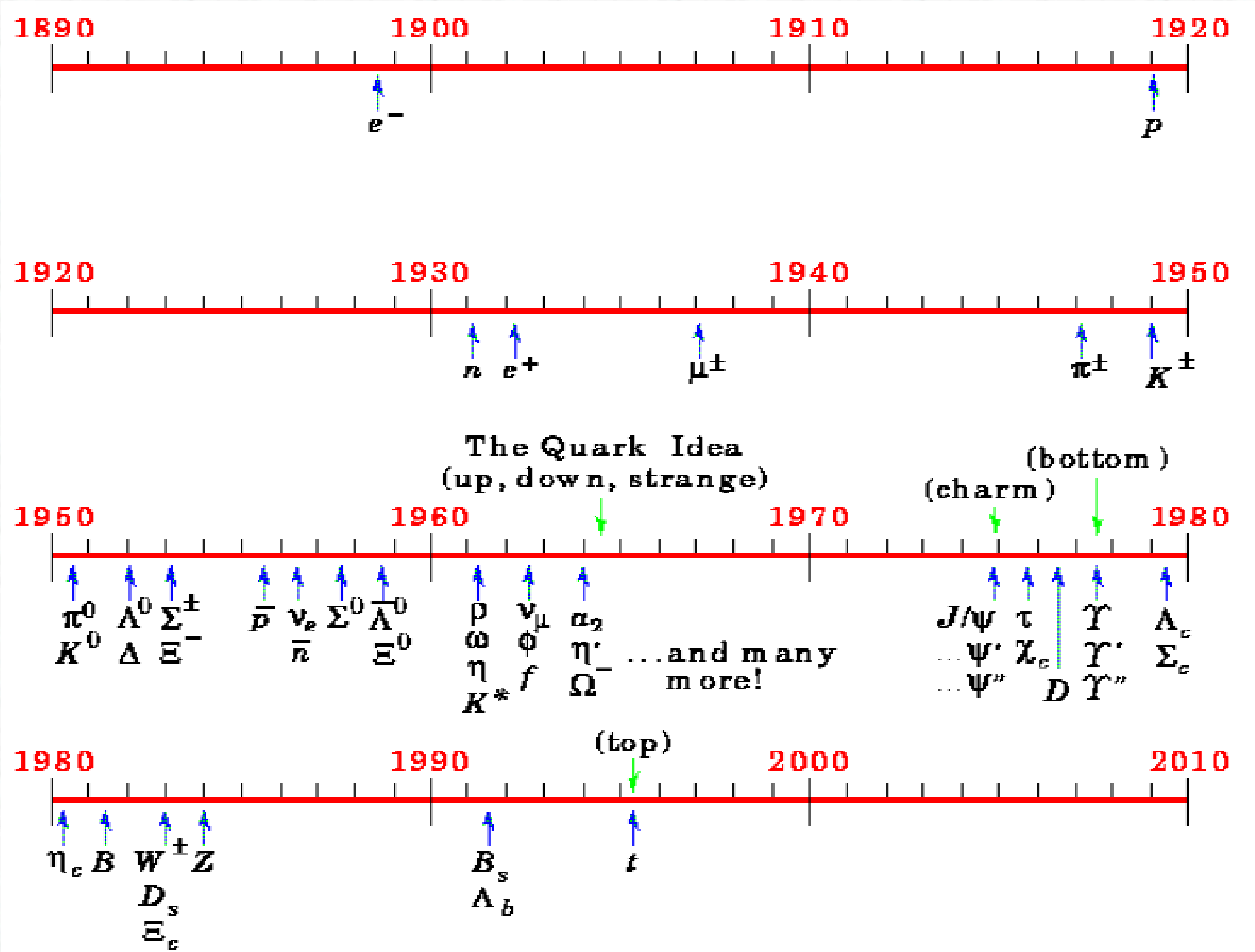
Fortgeschrittene Experimentalphysik für Lehramtsstudierende
Teil II: Kern- und Teilchenphysik

Prof. Markus Schumacher

Sommersemester 2013

Kapitel 7:Teilchenspektrum

Zeitachse der Teilchenentdeckungen bis 2010

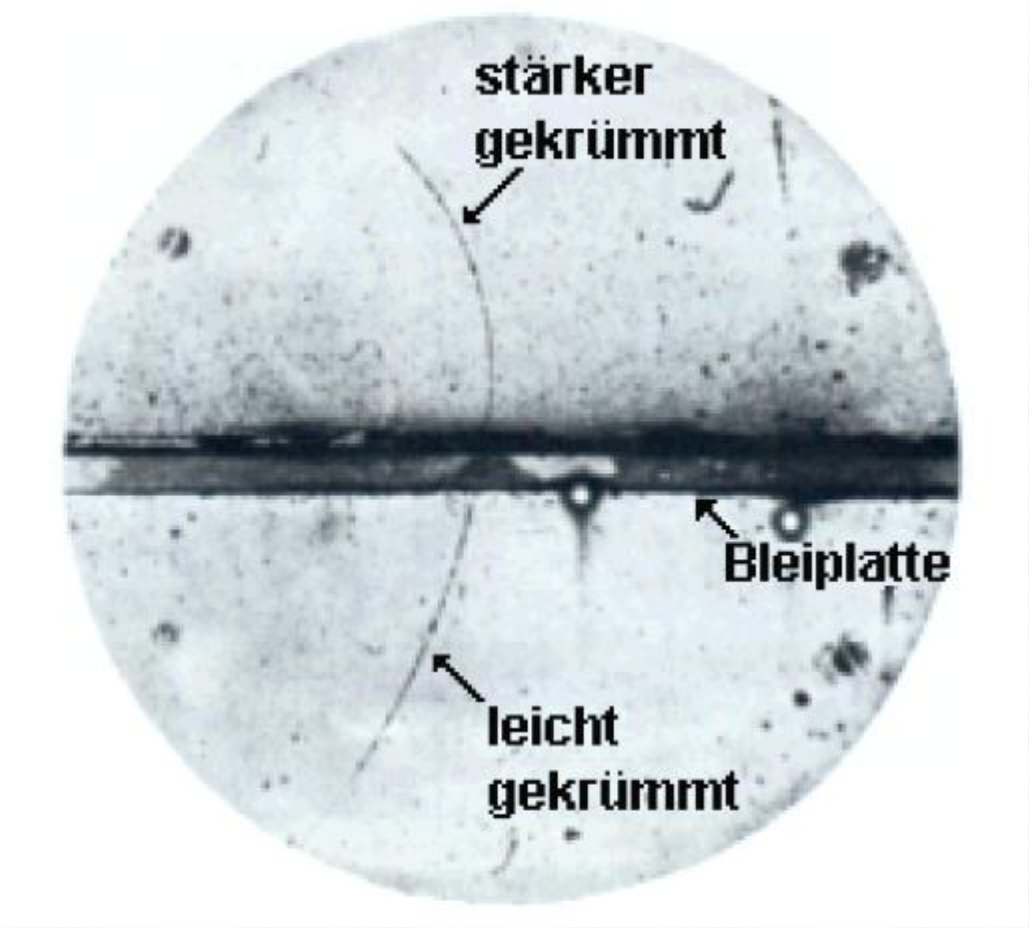


Entdeckung des Positrons

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 = $\frac{1}{2}\hbar$, stabil (im Vakuum), $\tau = \infty$



Entdeckung von Pion und Myon

Zerfälle:

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$$

$$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e} + \nu_{\mu}$$

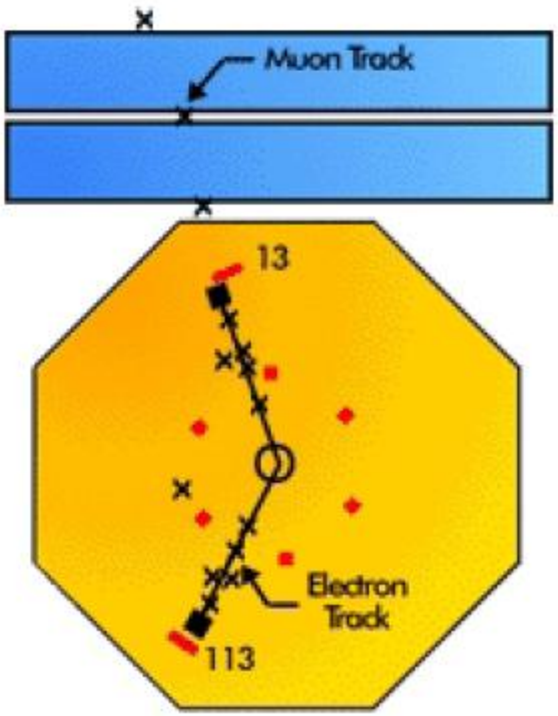
Entdeckung desTau-Leptons

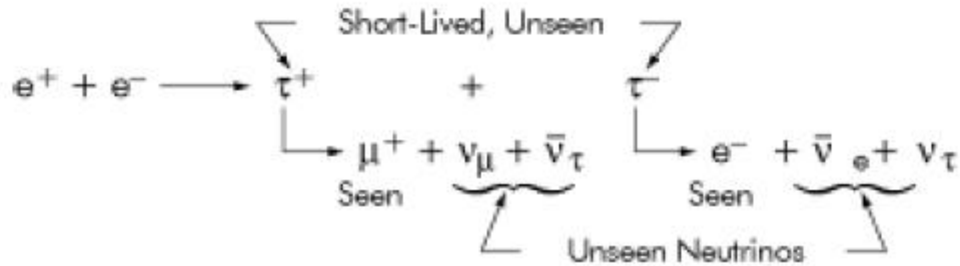
1975: Stanford Linear Accelerator Center, SLAC, M. Perl
Studium von e^+e^- Kollisionen mit dem MARK-I Detektor am Speicherring SPEAR (Strahlenergie 4 GeV)

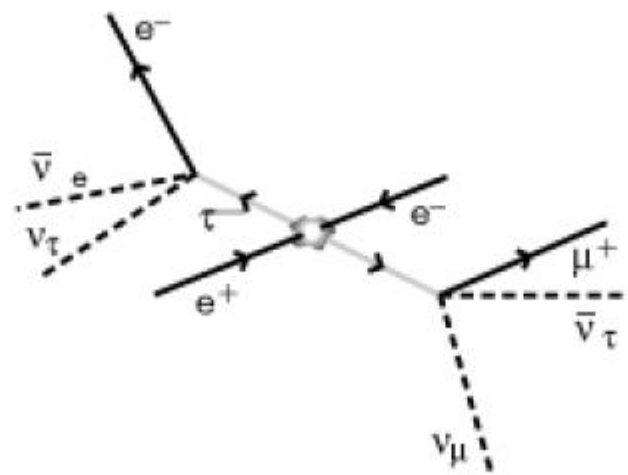
SLAC-PUB-1626
LBL-4228
August 1975
(T/E)

EVIDENCE FOR ANOMALOUS LEPTON PRODUCTION IN $e^+ - e^-$ ANNIHILATION*

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







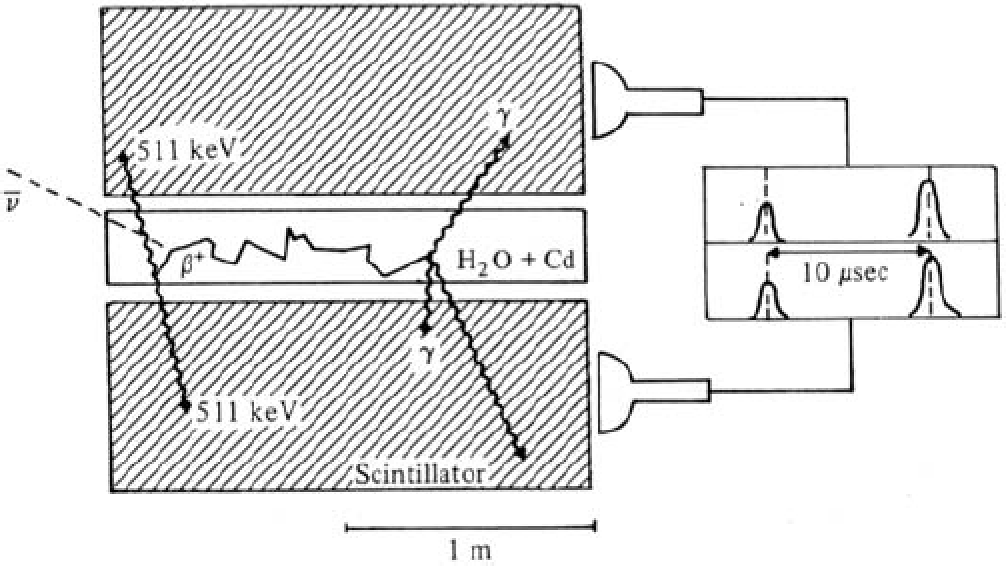
Nachweis des Elektron-Neutrinos

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

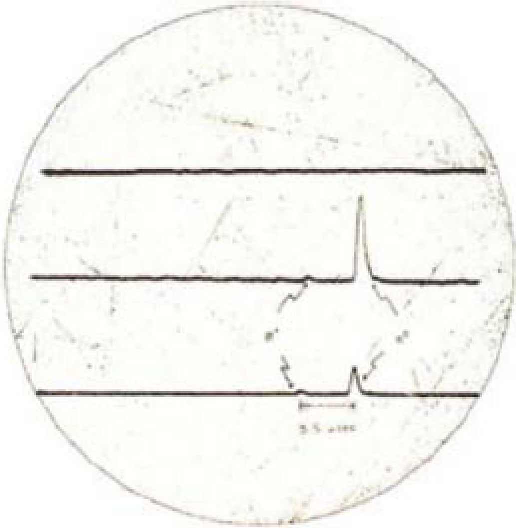
Abstand zum Detektor: 11 m, Neutrinofluss: $5 \cdot 10^{13}$ cm^{-2} sec^{-1}

Detektor: Flüssigszintillator mit Photomultiplier

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

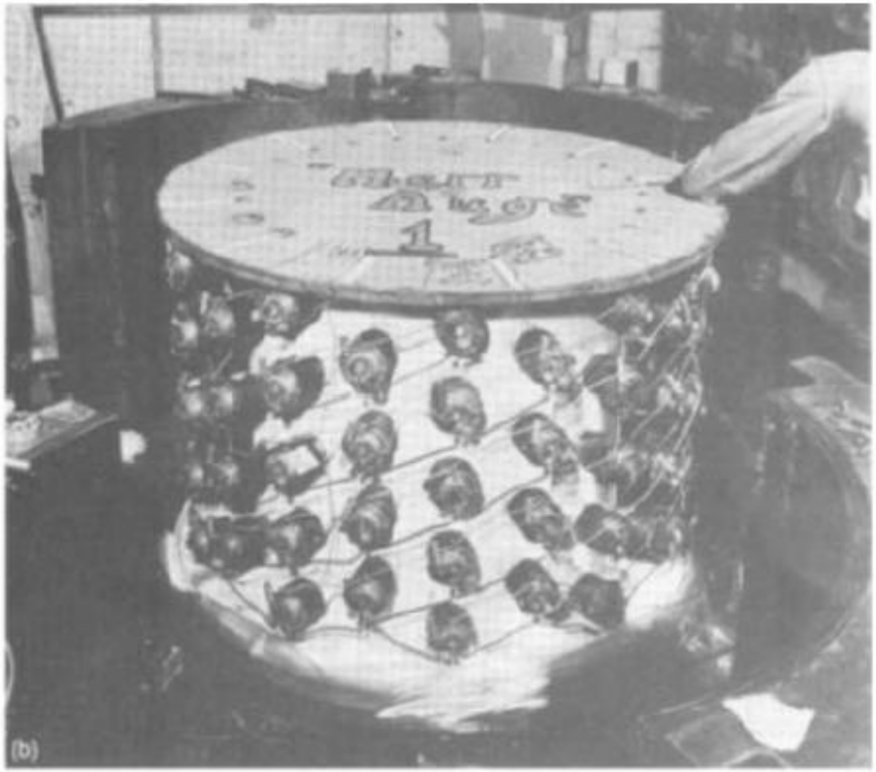


Das erste Neutrinosignal



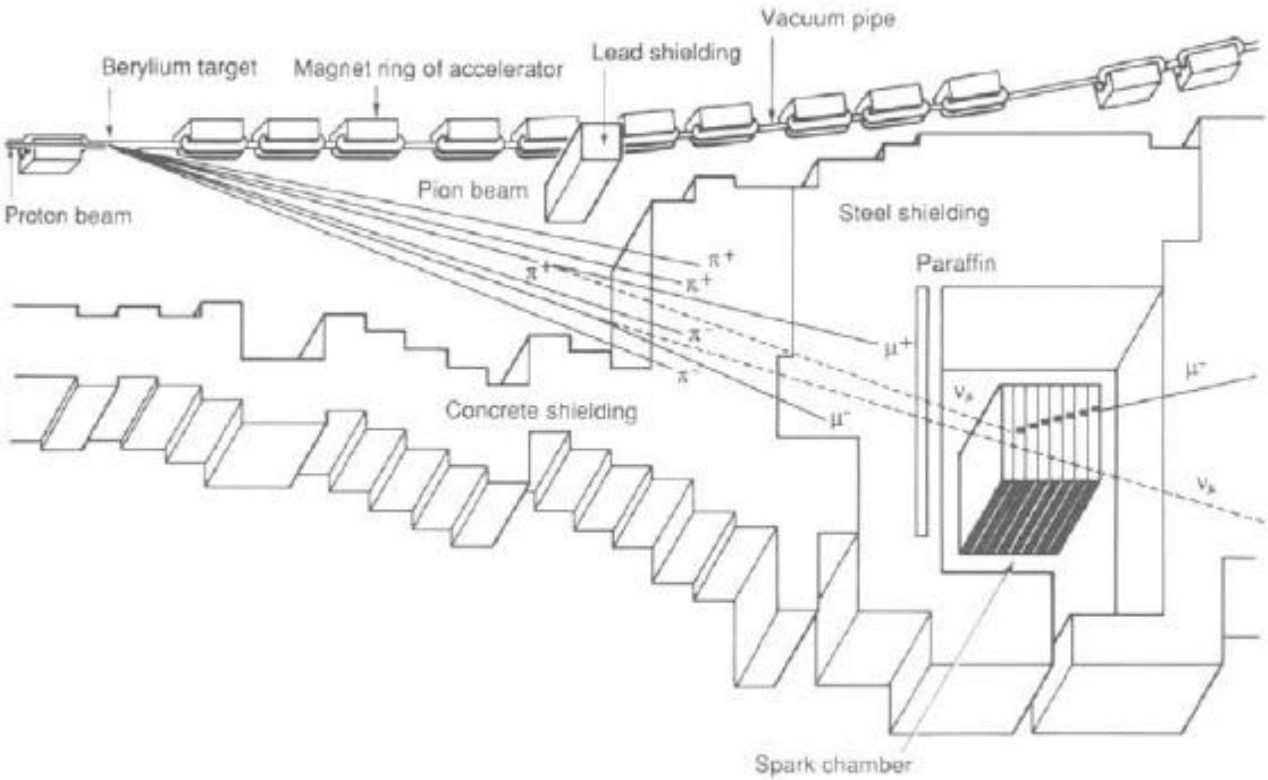
Nachweis des Elektron-Neutrinos

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)

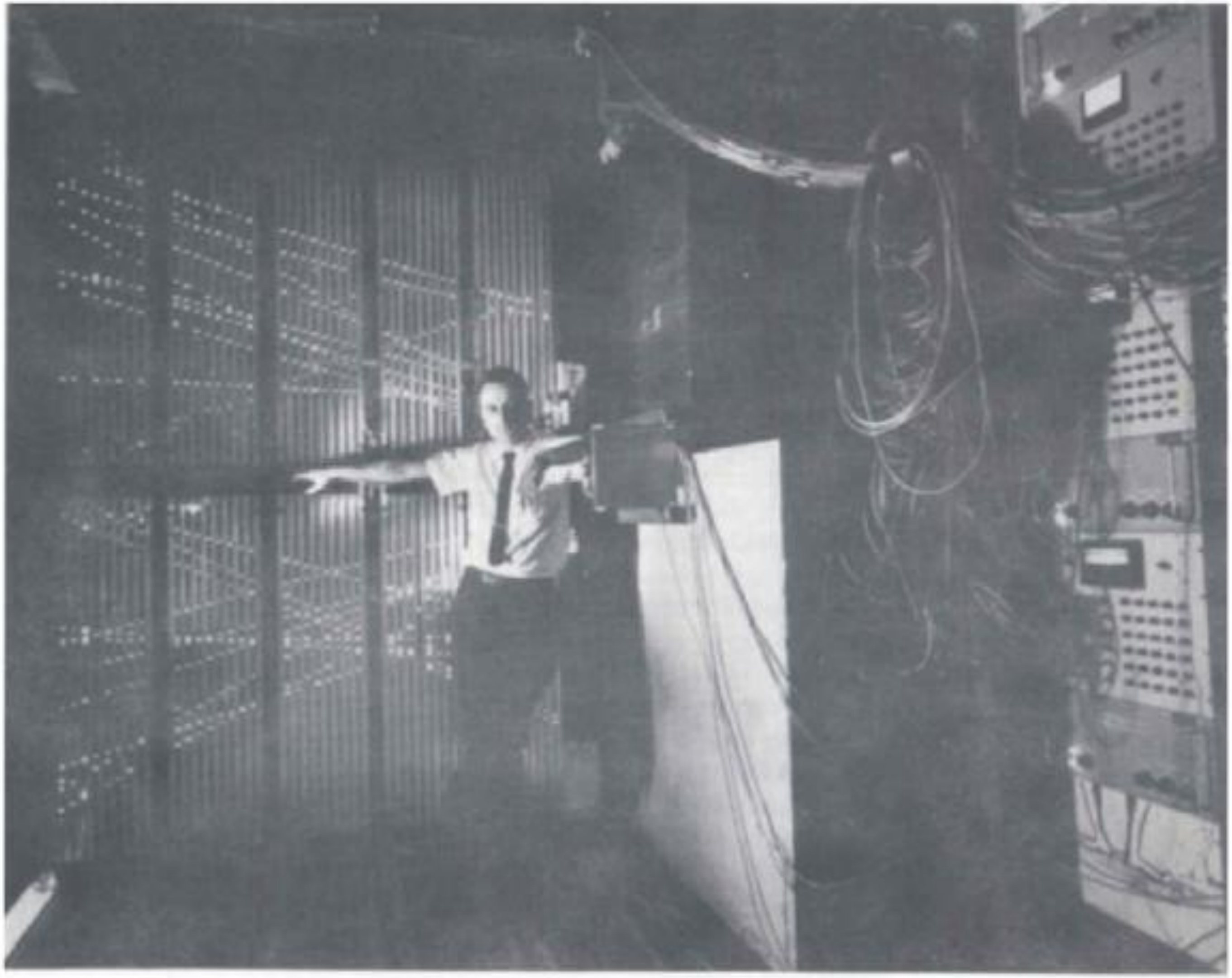
Nachweis, dass Myonneutrino ungleich Elektronneutrino



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.

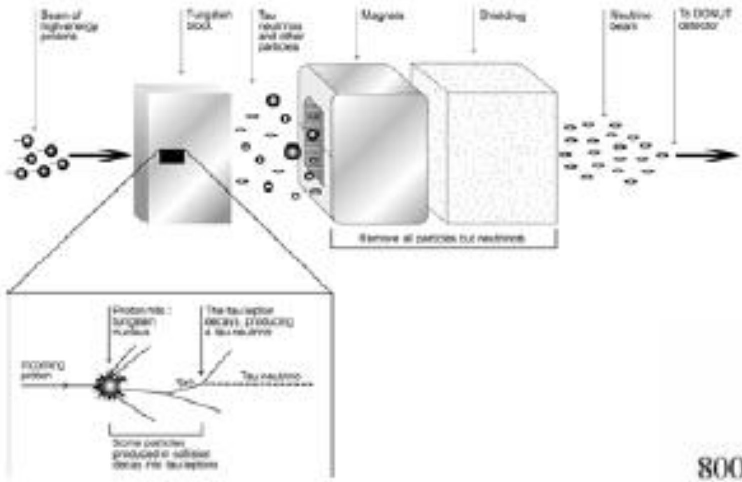
Nachweis das Myonneutrino ungleich Elektronneutrino



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.)

Nachweis das Tau-Neutrinos

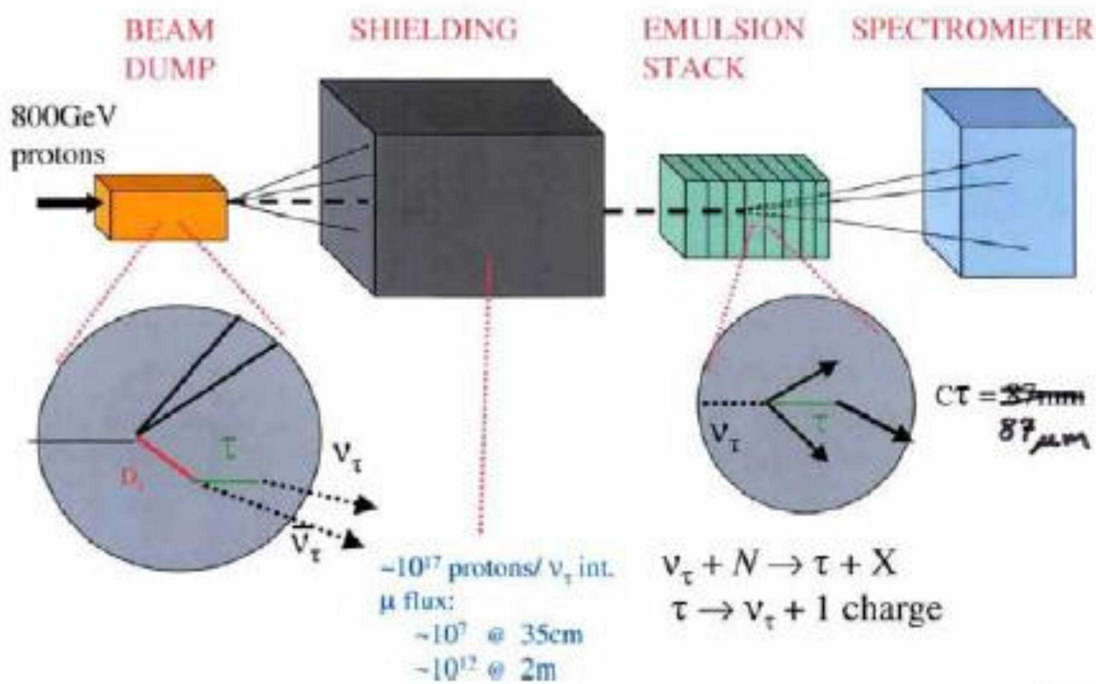
Creating a Tau Neutrino Beam



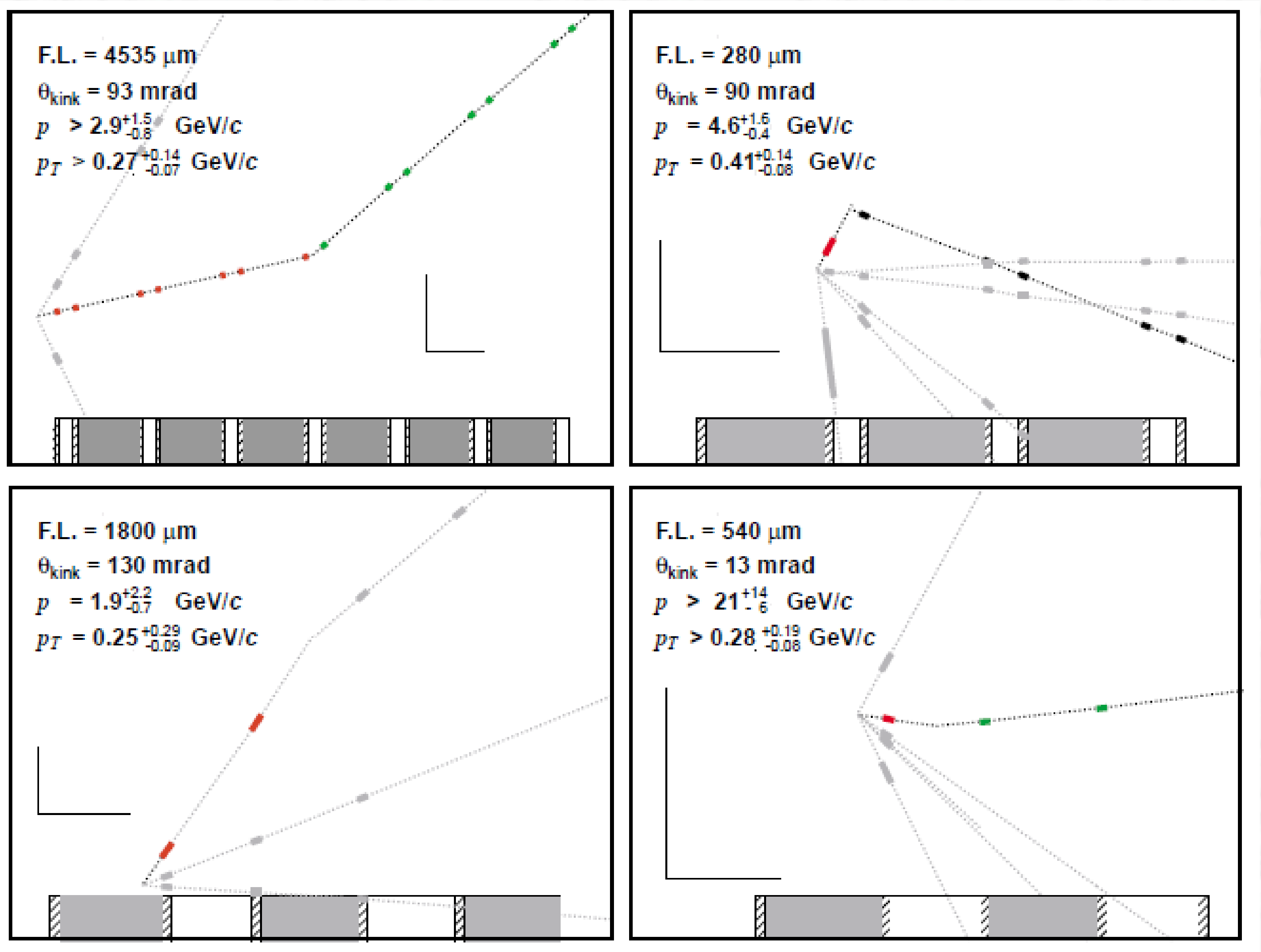
Observation of Tau Neutrino Interactions

DONUT Collaboration

December 14, 2000



Nachweis das Tau-Neutrinos



Hadronen: die Baryonen

Baryons (spin 1/2)

Baryon	Quark Content	Charge	Mass	Lifetime	Principal Decays
N p	uud	1	938.272	∞	–
N n	udd	0	939.565	885.7	$pe\bar{\nu}_e$
Λ	uds	0	1115.68	2.63×10^{-10}	$p\pi^-$, $n\pi^0$
Σ^+	uus	1	1189.37	8.02×10^{-11}	$p\pi^0$, $n\pi^+$
Σ^0	uds	0	1192.64	7.4×10^{-20}	$\Lambda\gamma$
Σ^-	dds	−1	1197.45	1.48×10^{-10}	$n\pi^-$
Ξ^0	uss	0	1314.8	2.90×10^{-10}	$\Lambda\pi^0$
Ξ^-	dss	−1	1321.3	1.64×10^{-10}	$\Lambda\pi^-$
Λ_c^+	udc	1	2286.5	2.00×10^{-13}	$pK\pi$, $\Lambda\pi\pi$, $\Sigma\pi\pi$

Baryons (spin 3/2)

Baryon	Quark Content	Charge	Mass	Lifetime	Principal Decays
Δ	uuu, uud, udd, ddd	2,1,0,−1	1232	5.6×10^{-24}	$N\pi$
Σ^*	uus, uds, dds	1,0,−1	1385	1.8×10^{-23}	$\Lambda\pi$, $\Sigma\pi$
Ξ^*	uss, dss	0,−1	1533	6.9×10^{-23}	$\Xi\pi$
Ω^-	sss	−1	1672	8.2×10^{-11}	ΛK^-, $\Xi\pi$

Hadronen: die Mesonen

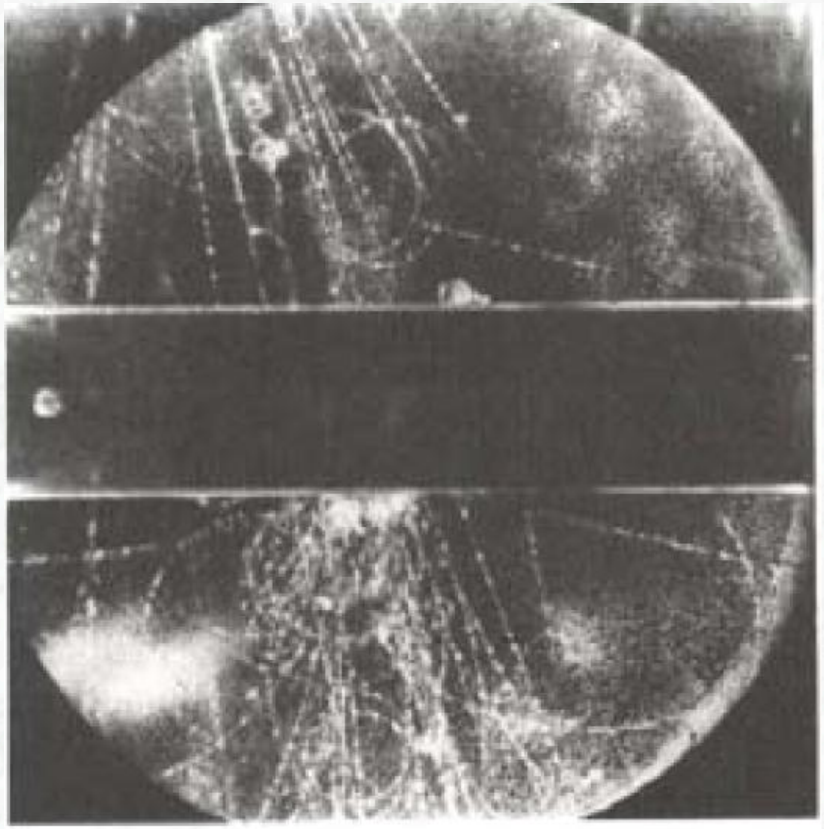
Pseudoscalar Mesons (spin 0)

Meson	Quark Content	Charge	Mass	Lifetime	Principal Decays
$\pi^\pm$	$u\bar{d}$, $d\bar{u}$	1,−1	139.570	2.60×10^{-8}	$\mu\nu_\mu$
π^0	$(u\bar{u} - d\bar{d})/\sqrt{2}$	0	134.977	8.4×10^{-17}	$\gamma\gamma$
$K^\pm$	$u\bar{s}$, $s\bar{u}$	1,−1	493.68	1.24×10^{-8}	$\mu\nu_\mu$, $\pi\pi$, $\pi\pi\pi$
$K^0, \overline{K}^0$	$d\bar{s}$, $s\bar{d}$	0	497.65	K_S^0 : 8.95×10^{-11} K_L^0 : 5.11×10^{-8}	$\pi\pi$ $\pi e\nu_e$, $\pi\mu\nu_\mu$, $\pi\pi\pi$
η	$(u\bar{u} + d\bar{d} - 2s\bar{s})/\sqrt{6}$	0	547.51	5.1×10^{-19}	$\gamma\gamma$, $\pi\pi\pi$
η'	$(u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$	0	957.78	3.2×10^{-21}	$\eta\pi\pi$, $\rho\gamma$
$D^\pm$	$c\bar{d}$, $d\bar{c}$	1,−1	1869.3	1.04×10^{-12}	$K\pi\pi$, $K\mu\nu_\mu$, $Ke\nu_e$
$D^0, \overline{D}^0$	$c\bar{u}$, $u\bar{c}$	0	1864.5	4.1×10^{-13}	$K\pi\pi$, $Ke\nu_e$, $K\mu\nu_\mu$
$D_s^\pm$	$c\bar{s}$, $s\bar{c}$	1,−1	1968.2	5.0×10^{-13}	$\eta\rho$, $\phi\pi\pi$, $\phi\rho$
$B^\pm$	$u\bar{b}$, $b\bar{u}$	1,−1	5279.0	1.6×10^{-12}	$D^*\ell\nu_\ell$, $D\ell\nu_\ell$, $D^*\pi\pi\pi$
$B^0, \overline{B}^0$	$d\bar{b}$, $b\bar{d}$	0	5279.4	1.5×10^{-12}	$D^*\ell\nu_\ell$, $D\ell\nu_\ell$, $D^*\pi\pi$

Vector Mesons (spin 1)

Meson	Quark Content	Charge	Mass	Lifetime	Principal Decays
ρ	$u\bar{d}$, $(u\bar{u} - d\bar{d})/\sqrt{2}$, $d\bar{u}$	1,0,-1	775.5	4×10^{-24}	$\pi\pi$
K^*	$u\bar{s}$, $d\bar{s}$, $s\bar{d}$, $s\bar{u}$	1,0,-1	894	1×10^{-23}	$K\pi$
ω	$(u\bar{u} + d\bar{d})/\sqrt{2}$	0	782.6	8×10^{-23}	$\pi\pi\pi$, $\pi\gamma$
ψ	$c\bar{c}$	0	3097	7×10^{-21}	e^+e^-, $\mu^+\mu^-$, 5π, 7π
D^*	$c\bar{d}$, $c\bar{u}$, $u\bar{c}$, $d\bar{c}$	1,0,-1	2008	3×10^{-21}	$D\pi$, $D\gamma$
Υ	$b\bar{b}$	0	9460	1×10^{-20}	e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$

Beobachtung seltsamer Teilchen K0 →Pi+ Pi-



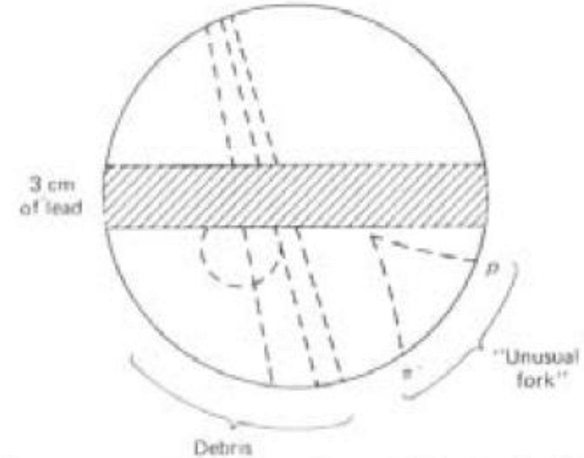
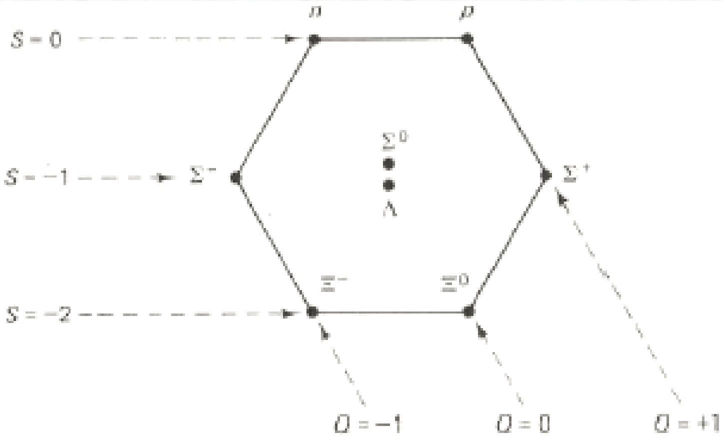
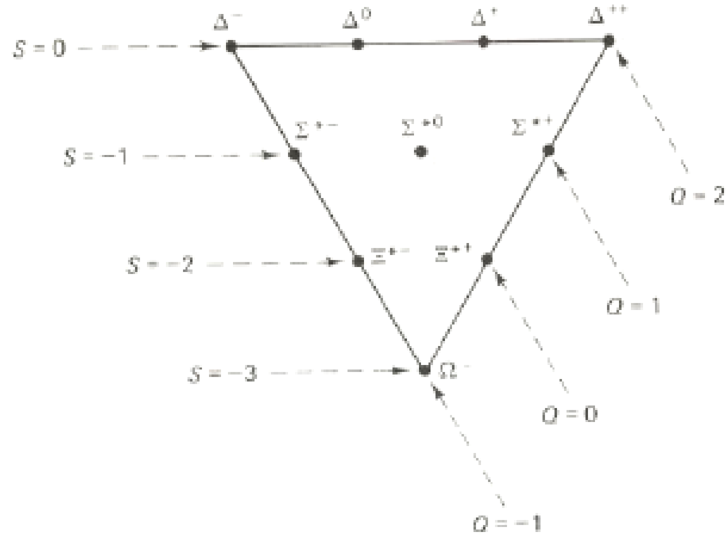


Figure 1.8 The first strange particle. Cosmic rays strike a lead plate, producing a K^0, which subsequently decays into a pair of charged pions. (Photo courtesy of Prof. G. D. Rochester. Reprinted by permission from *Nature* **160,** 855. Copyright © 1947, Macmillan Journals Limited.)

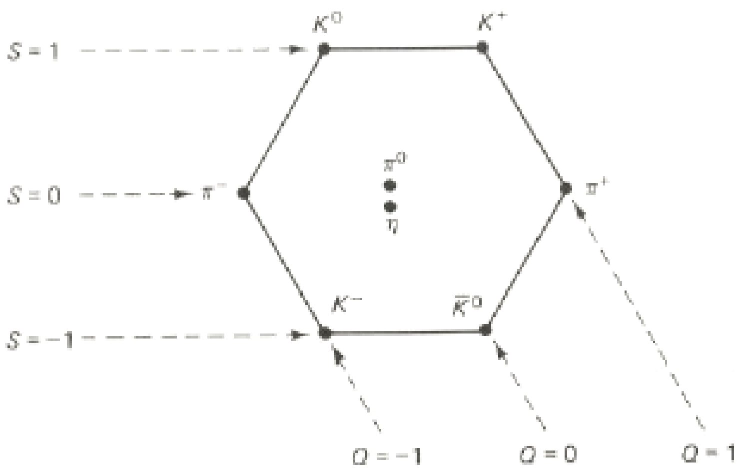
Die Hadronenmultipletts



Das Baryonen-Oktett

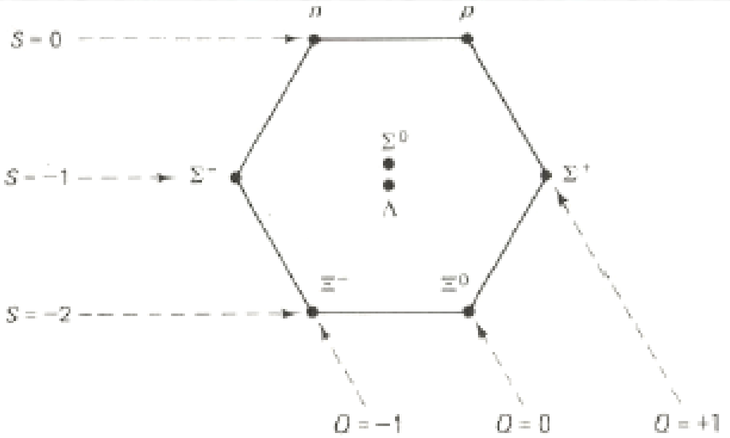


Das Baryonen-Dekuplett

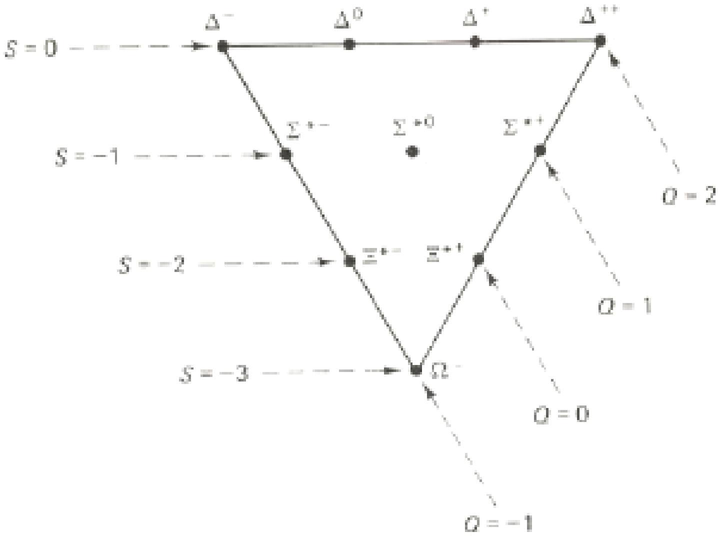


Das Mesonen-Oktett

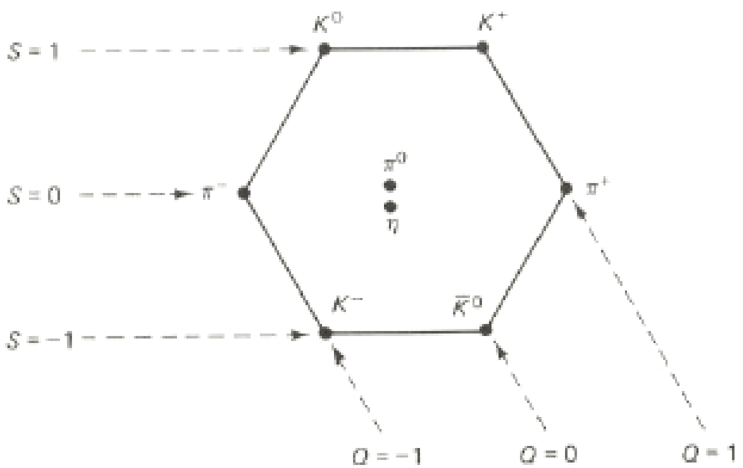
Die Hadronenmultipletts



Das Baryonen-Oktett



Das Baryonen-Dekuplett



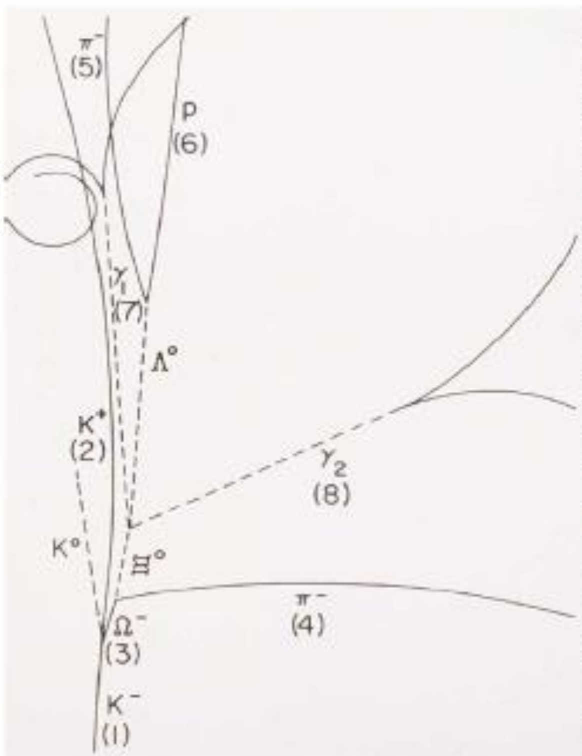
Das Mesonen-Oktett

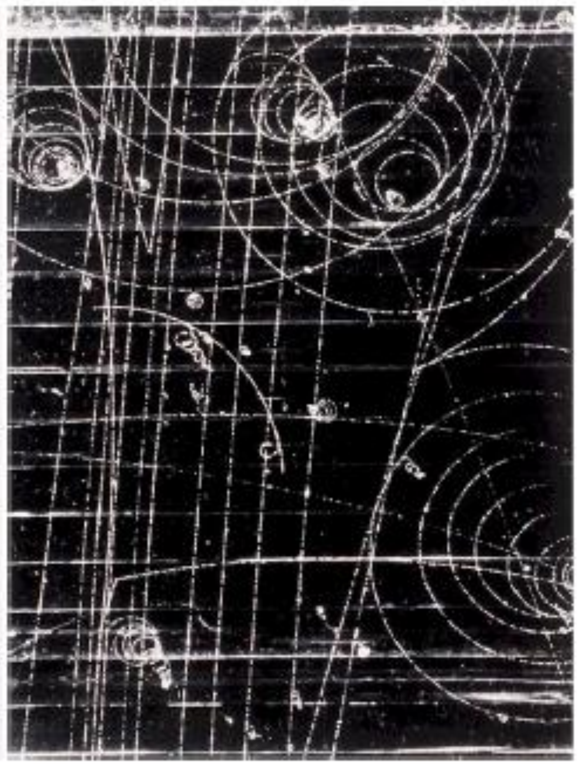
Entdeckung des Omega Minus

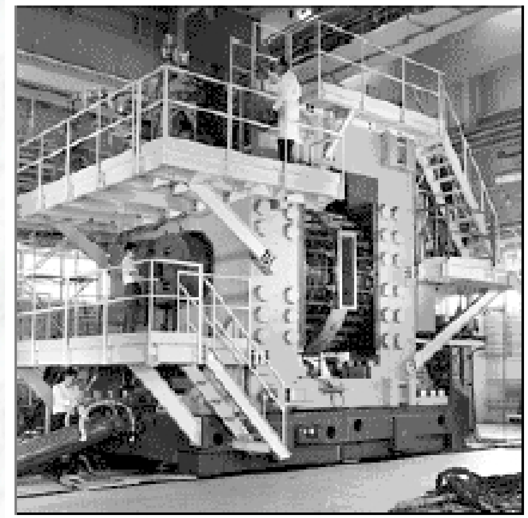
1964: Brookhaven, AGS-Beschleuniger
80 Zoll Blasenkammer, flüssiger Wasserstoff

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

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







The 80-inch Bubble Chamber

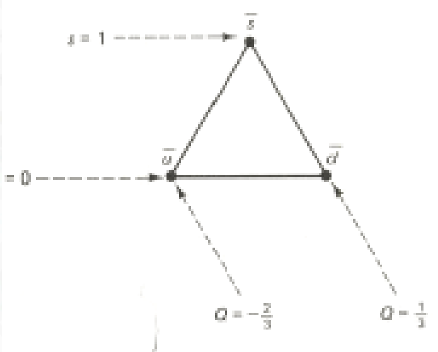
Das Quarkmodell

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	??

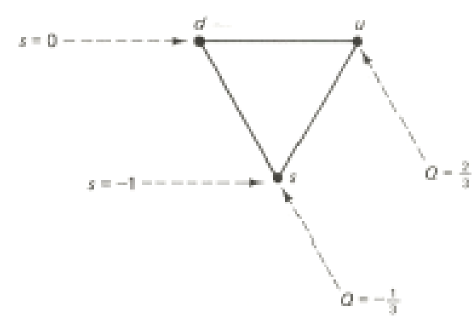
THE BARYON DECUPLET

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 Quarkmodell

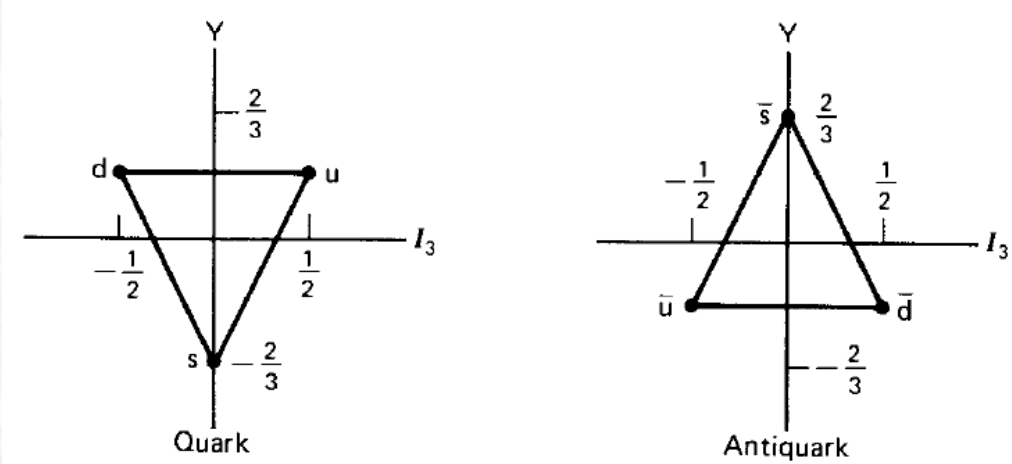


Fig. 2.4 $SU(3)$ quark and antiquark multiplets; $Y \equiv B + S$.

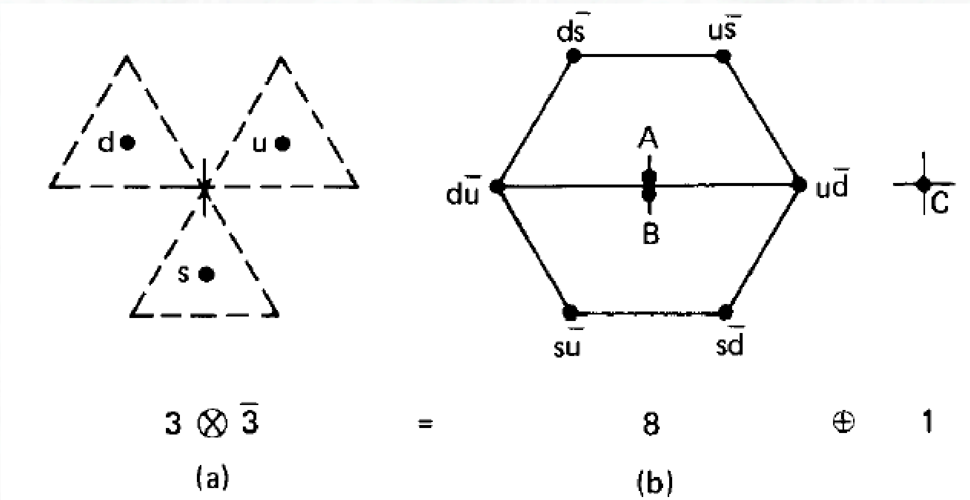


Fig. 2.5 The quark content of the meson nonet, showing the $SU(3)$ decomposition in the I_3, Y plane.

Das Quarkmodell

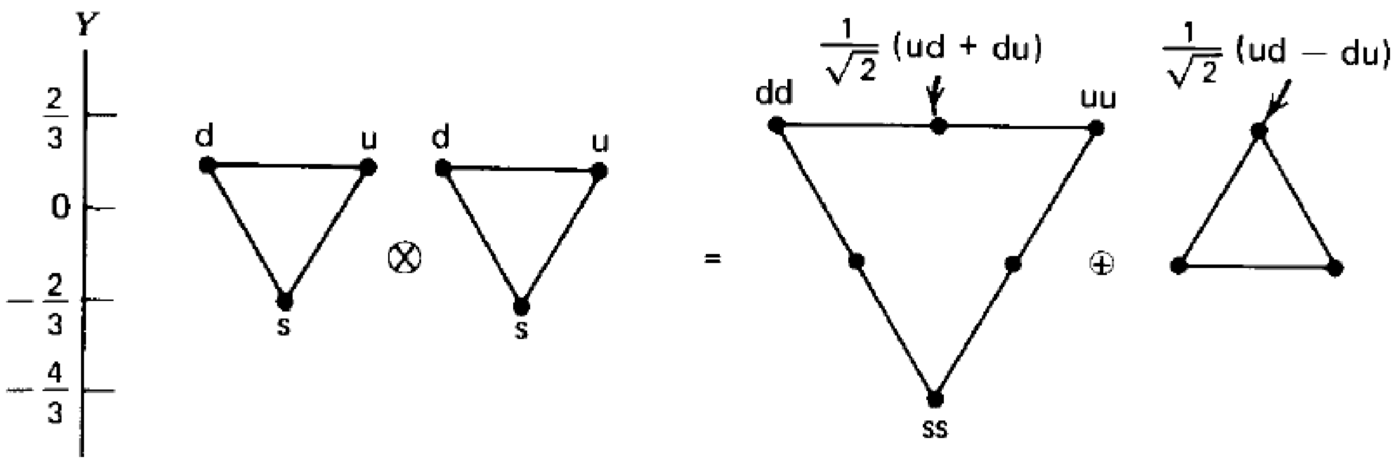


Fig. 2.6 The qq $SU(3)$ multiplets; $3 \otimes 3 = 6 \oplus \bar{3}$.

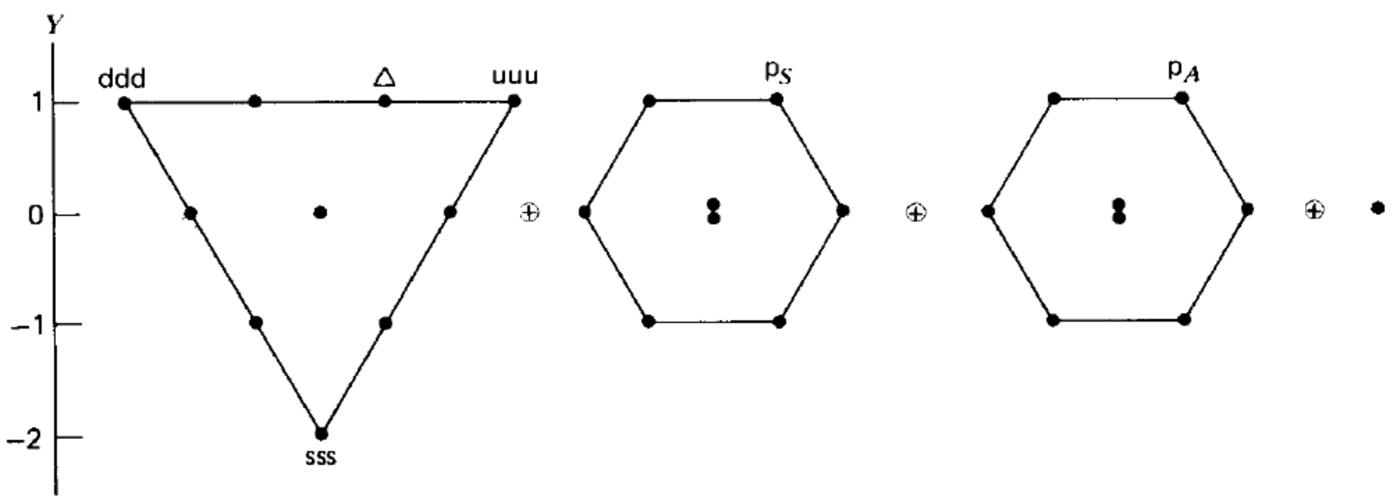


Fig. 2.7 The qqq $SU(3)$ multiplets; $3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$.

Das Quarkmodell

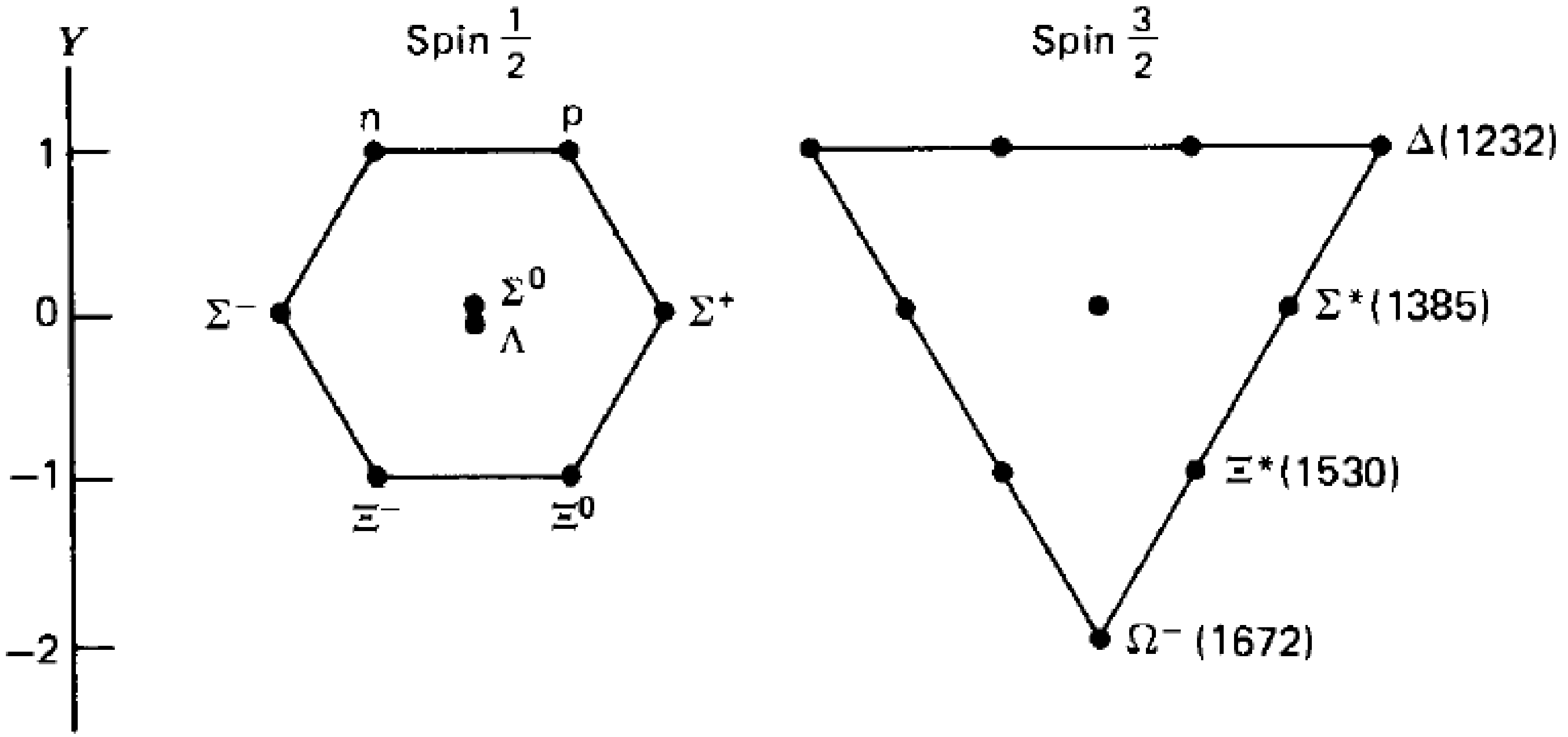


Fig. 2.8 Ground-state baryons: (8, 2) + (10, 4).

Entdeckung des J/Psi

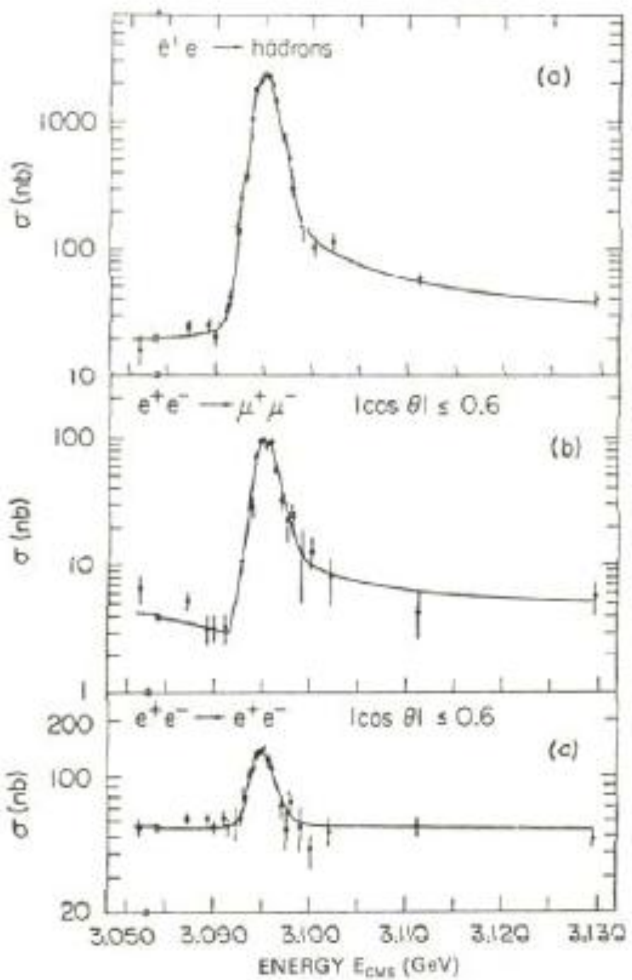


Fig. 5.10 Results of Augustin *et al.* (1974) showing the observation of the ψ/J resonance at mass 3.1 GeV, produced in e^+e^- annihilation at the SPEAR storage ring, SLAC.
(aus Ref. [8])

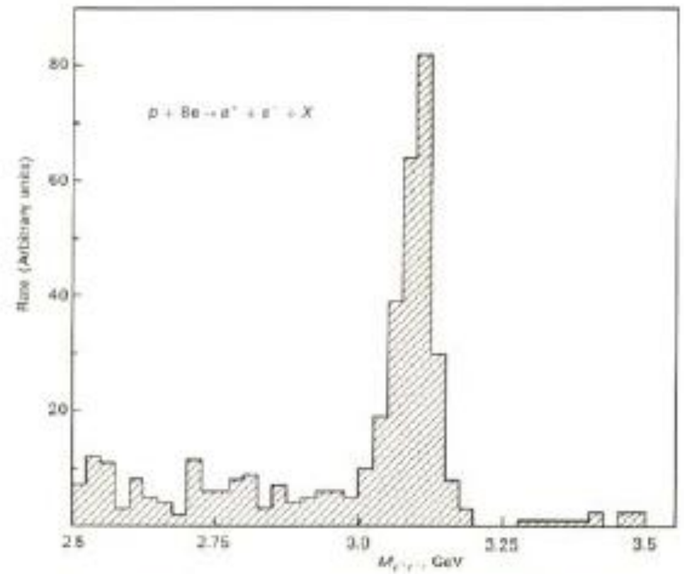
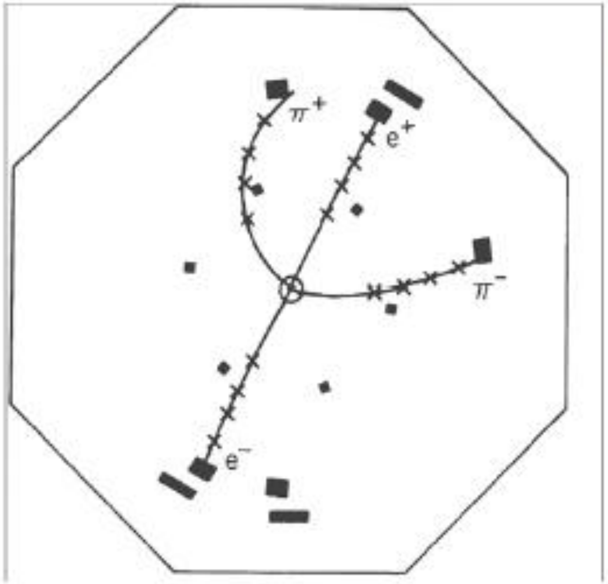


Fig. 5.11 Results of Aubert *et al.* (1974) indicating the narrow resonance ψ/J in the invariant-mass distribution of e^+e^- pairs produced in inclusive reactions of protons with a beryllium target. The experiment was carried out with the 28-GeV AGS at Brookhaven National Laboratory.
(aus Ref. [8])

Samuel S. Ting (1974)

Entdeckung des J/Psi



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%

Mesonen im 4-Flavour-Quark-Modell

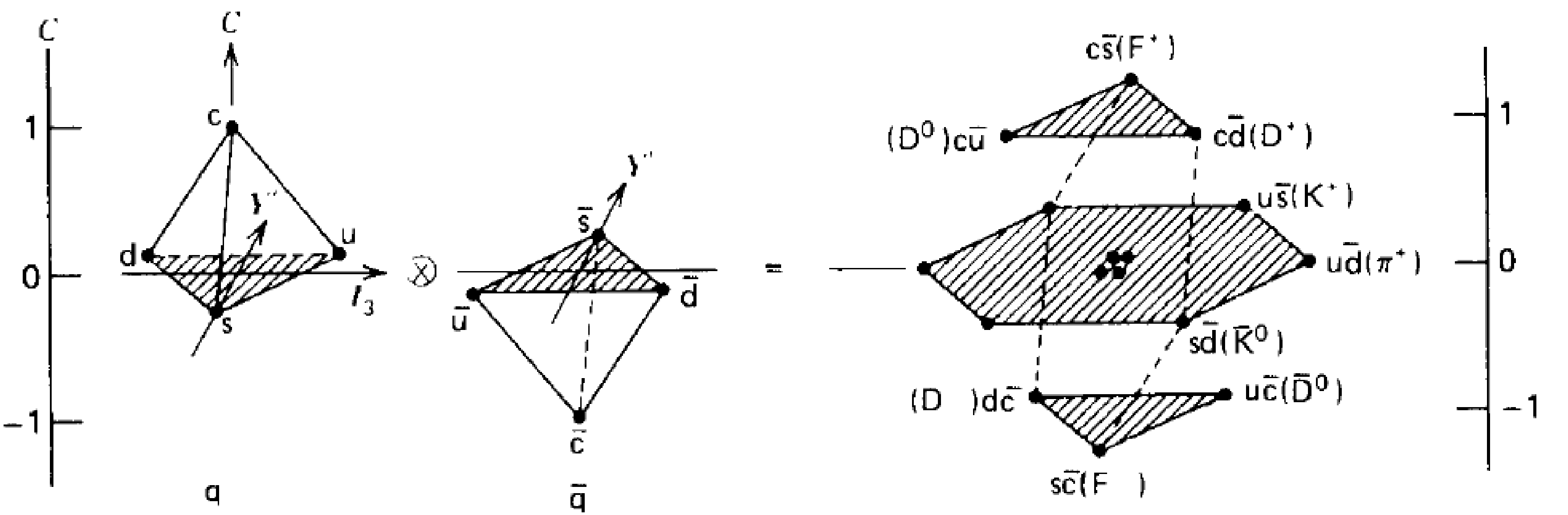
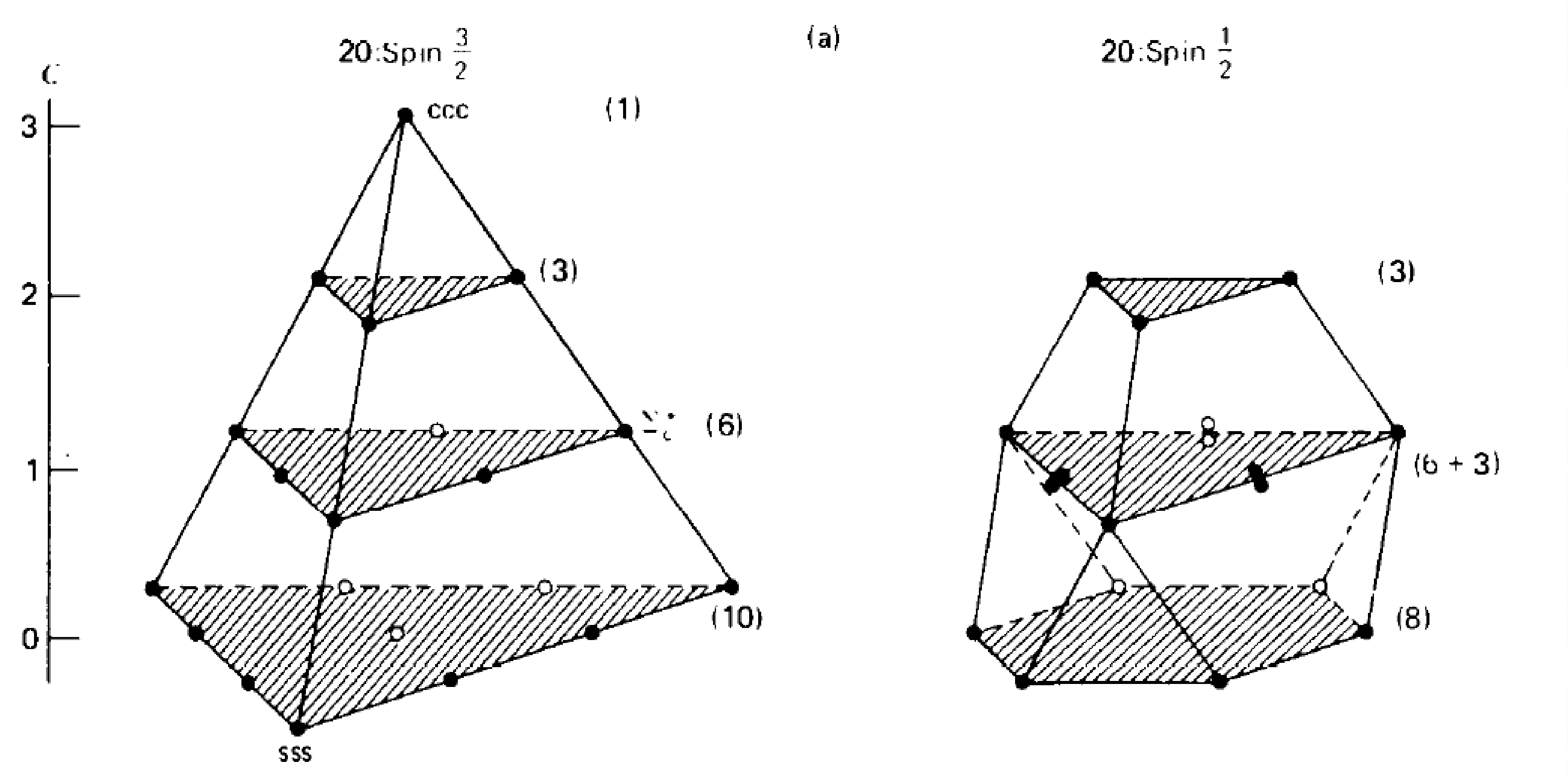
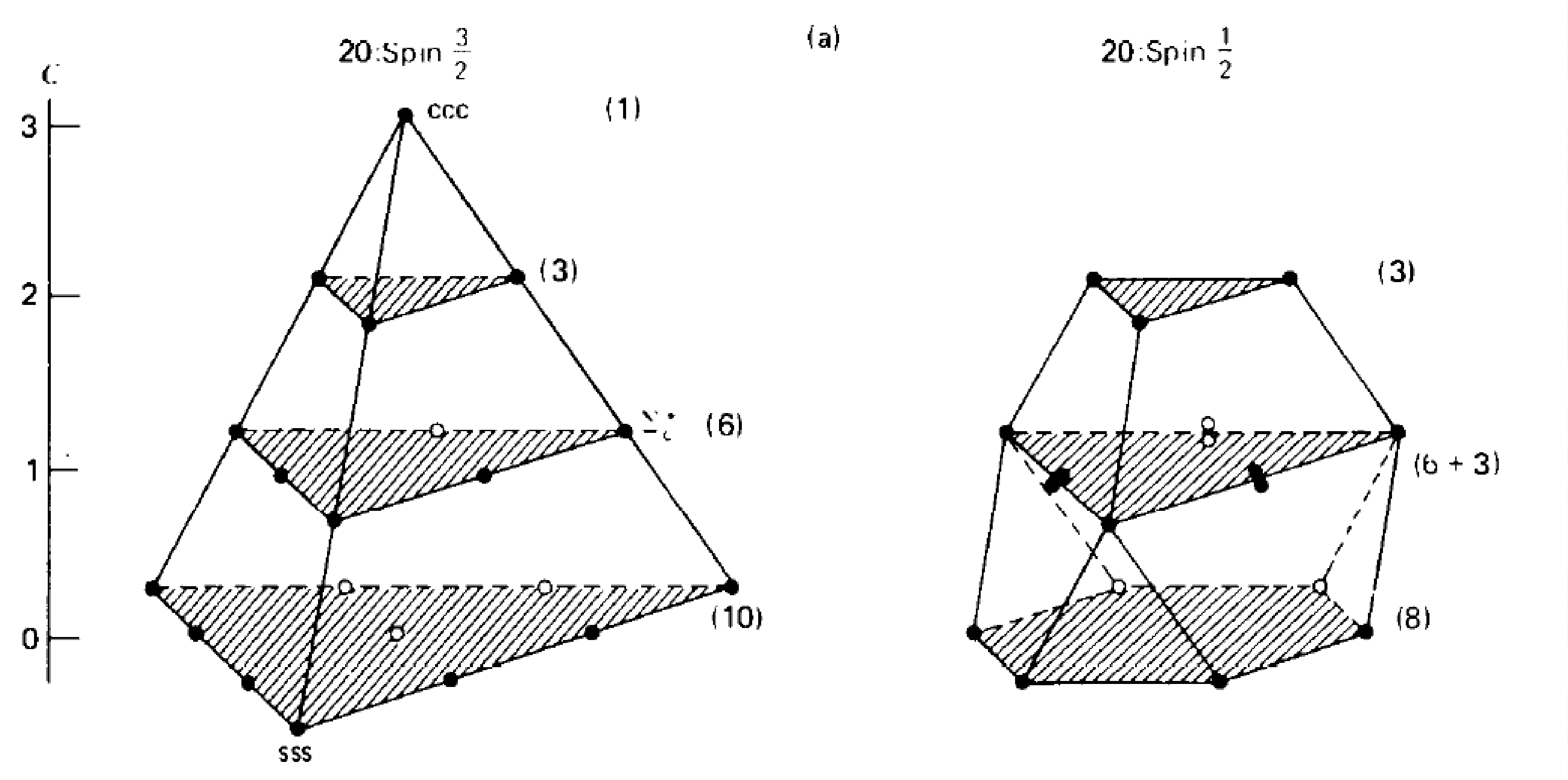


Fig. 2.12 The 16 meson states made from u, d, s, c quarks, plotted in (I_3, Y', C) space with $Y' = Y - \frac{4}{3}C$. Some members of the $J^P = 0^-$ multiplet are indicated.

Baryonen im 4-Flavour-Quark-Modell



Baryonen im 4-Flavour-Quark-Modell



Entdeckung des Upsilon

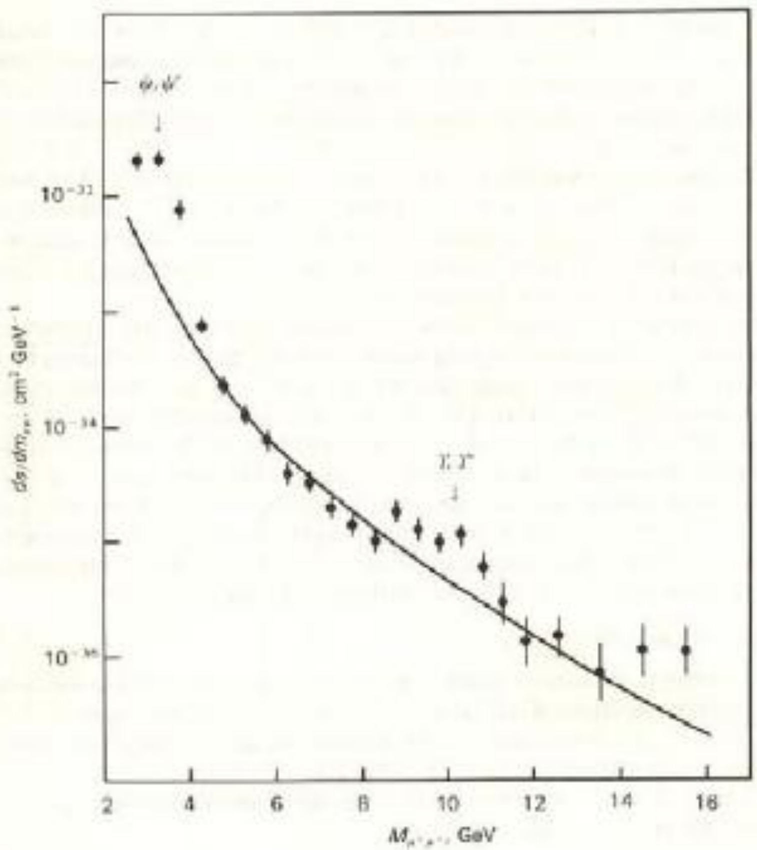


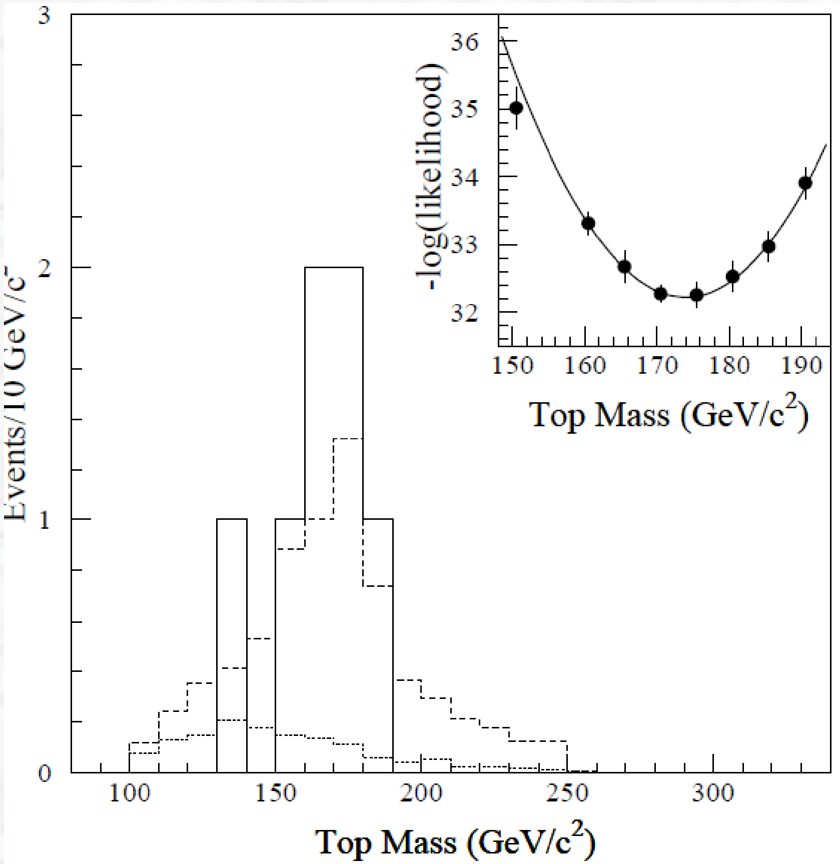
Fig. 5.16 First evidence for the upsilon resonances Υ, Υ', obtained by Herb *et al.* (1977) from the spectrum of muon pairs observed in 400-GeV proton-nucleus collisions at Fermilab, near Chicago. The enhancement due to these resonances stands out against the rapidly falling continuum background. (aus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

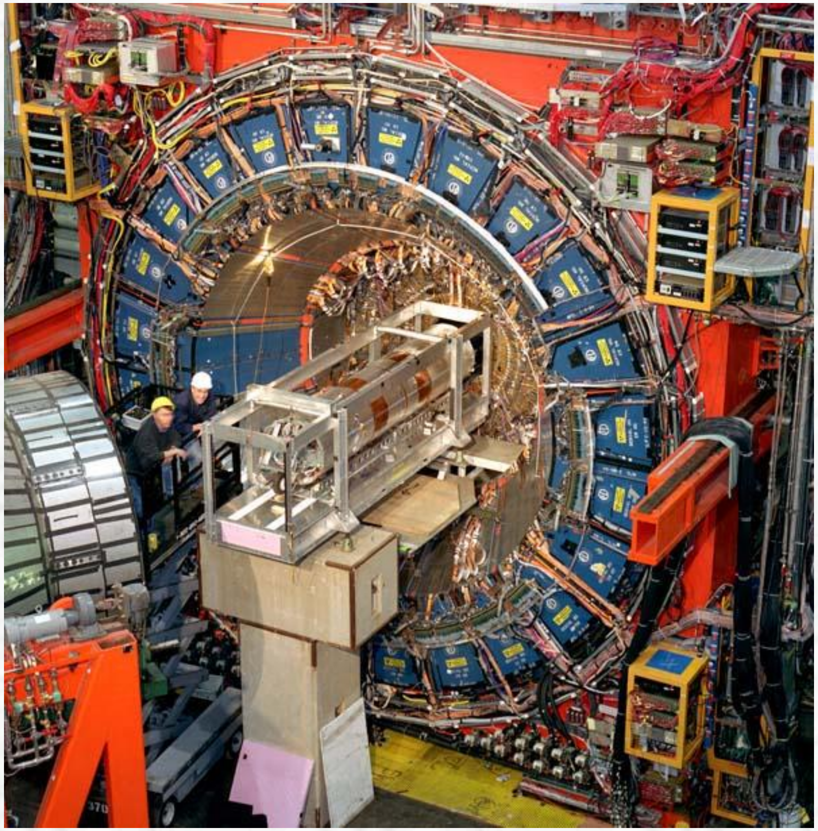
L. Ledermann et al.,
Fermilab (1977)

Entdeckung des Top-Quarks 1994 am Tevatron

FERMILAB-PUB-94/116-E
CDF/PUB/TOP/PUBLIC/2595
May 16, 1994

Evidence for Top Quark Production in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV





$$M_{top} = 174 \pm 10^{+13}_{-12}$$

Übersicht über Quarks

Quarks (spin 1/2)

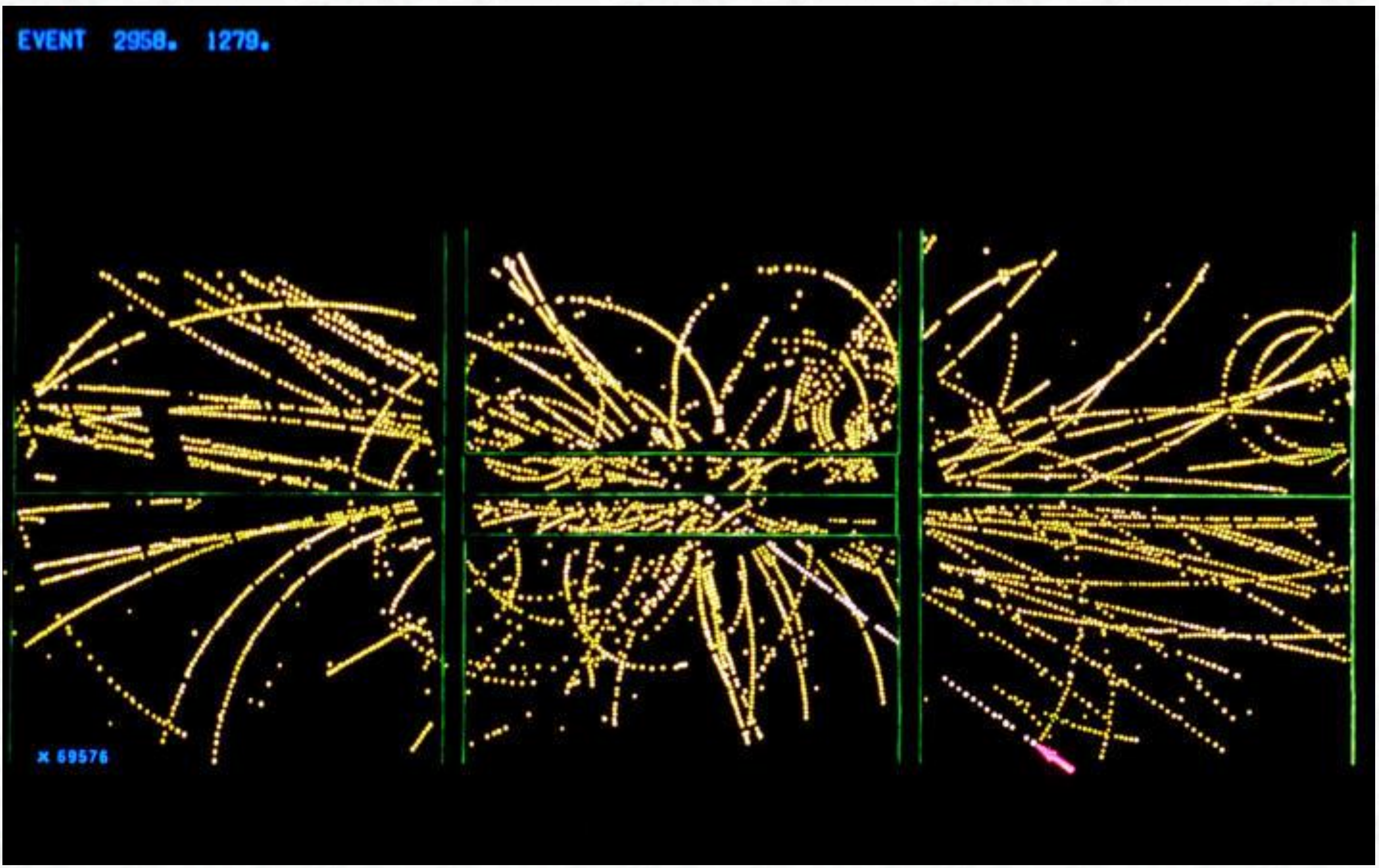
Generation	Flavor	Charge	Mass* MeV
first	*d* (down)	−1/3	7
	u (up)	2/3	3
second	*s* (strange)	−1/3	120
	c (charm)	2/3	1200
third	*b* (bottom)	−1/3	4300
	t (top)	2/3	174000

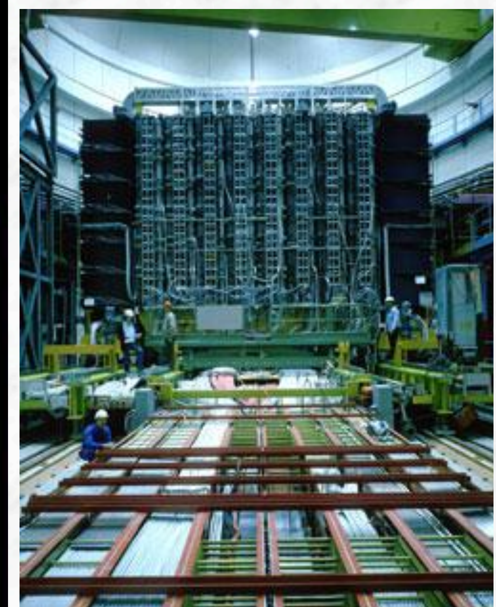
Entdeckung des W Bosons

EXPERIMENTAL OBSERVATION OF ISOLATED LARGE TRANSVERSE ENERGY ELECTRONS

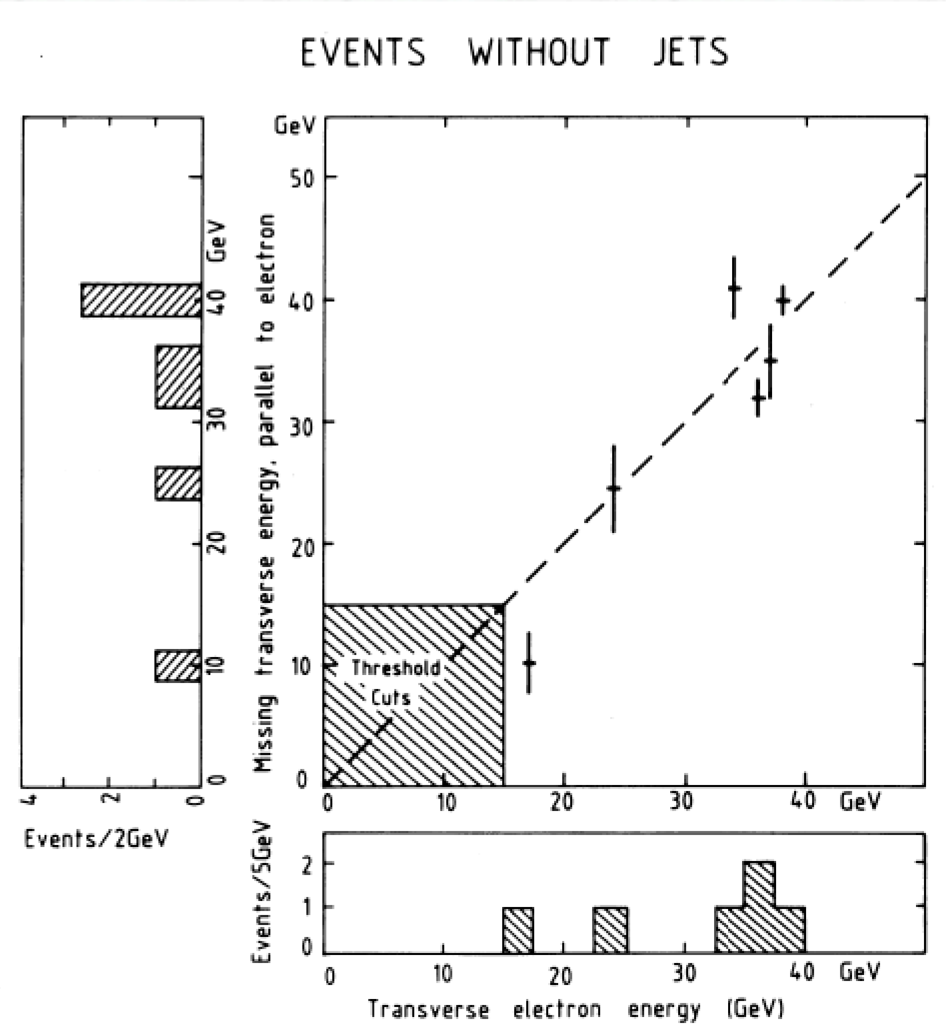
WITH ASSOCIATED MISSING ENERGY AT $\sqrt{s}$ = 540 GeV

UA1 Collaboration, CERN, Geneva, Switzerland

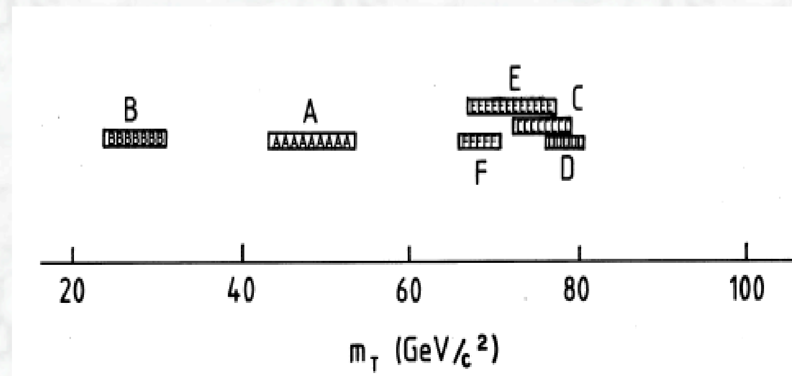




Entdeckung des W Bosons

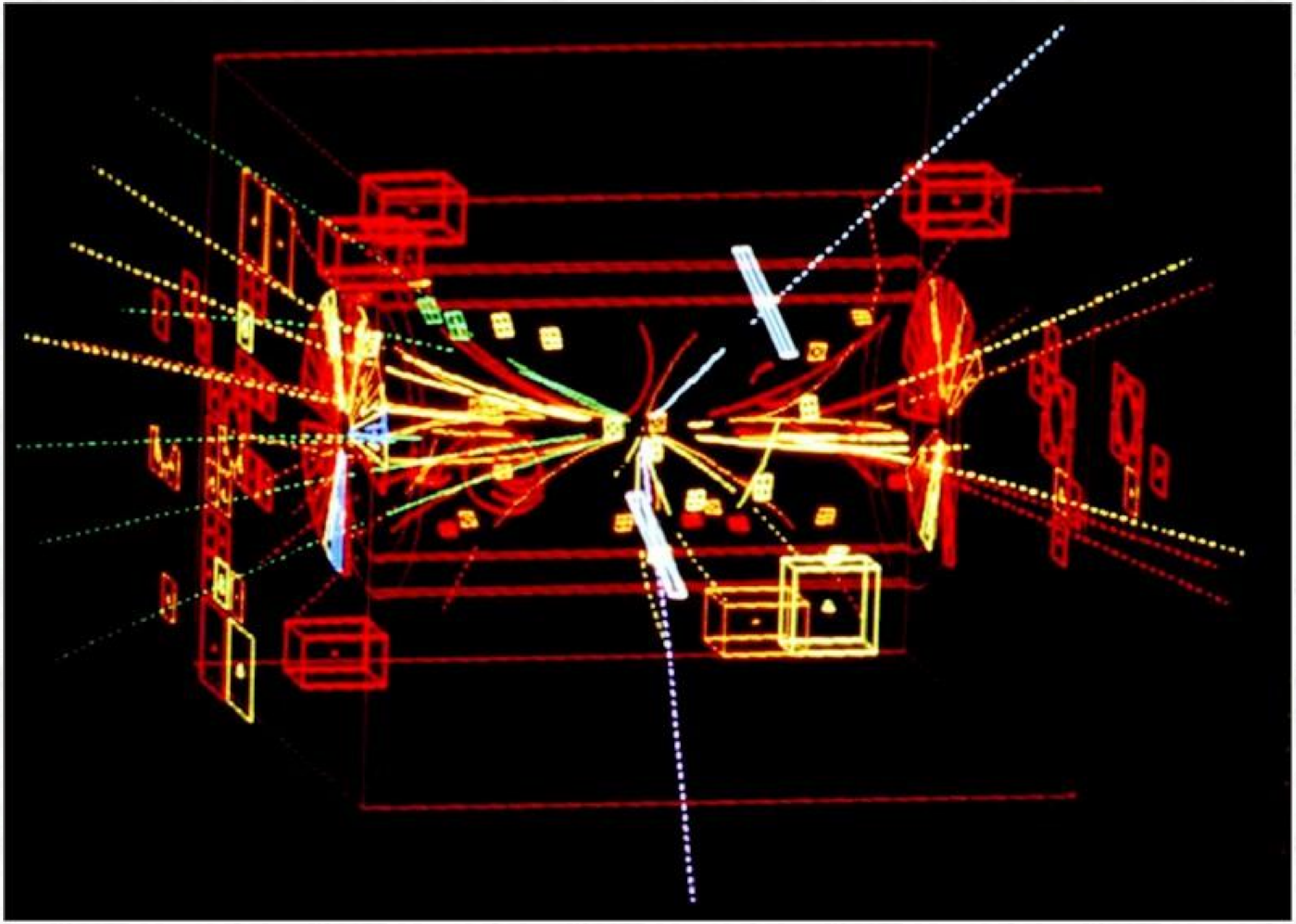


$$m_T^2 = 2p_T^{(e)}p_T^{(\nu)}(1 - \cos\phi_{\nu_e})$$



$$m_W = 81 \pm 5 \ \mathrm{GeV}/c^2$$

Entdeckung des Z Bosons

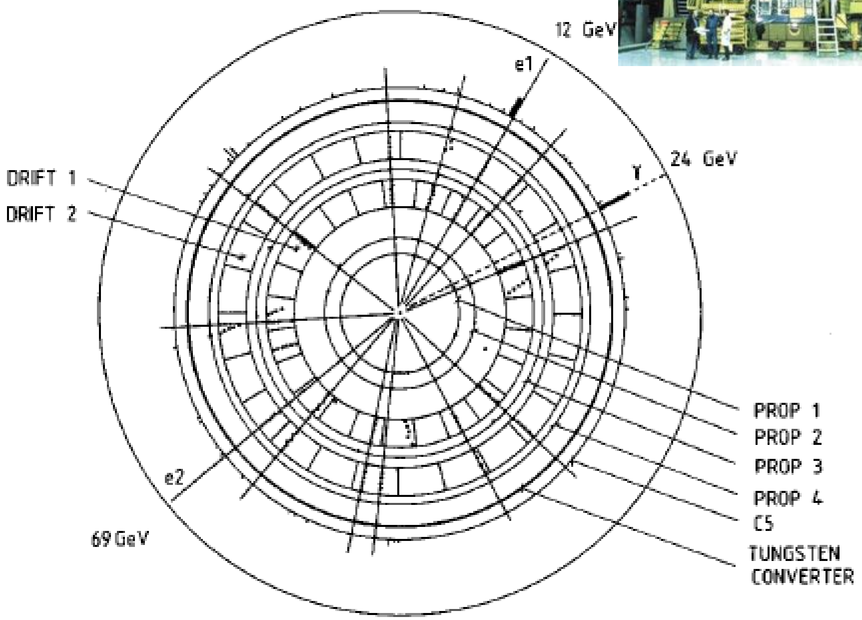


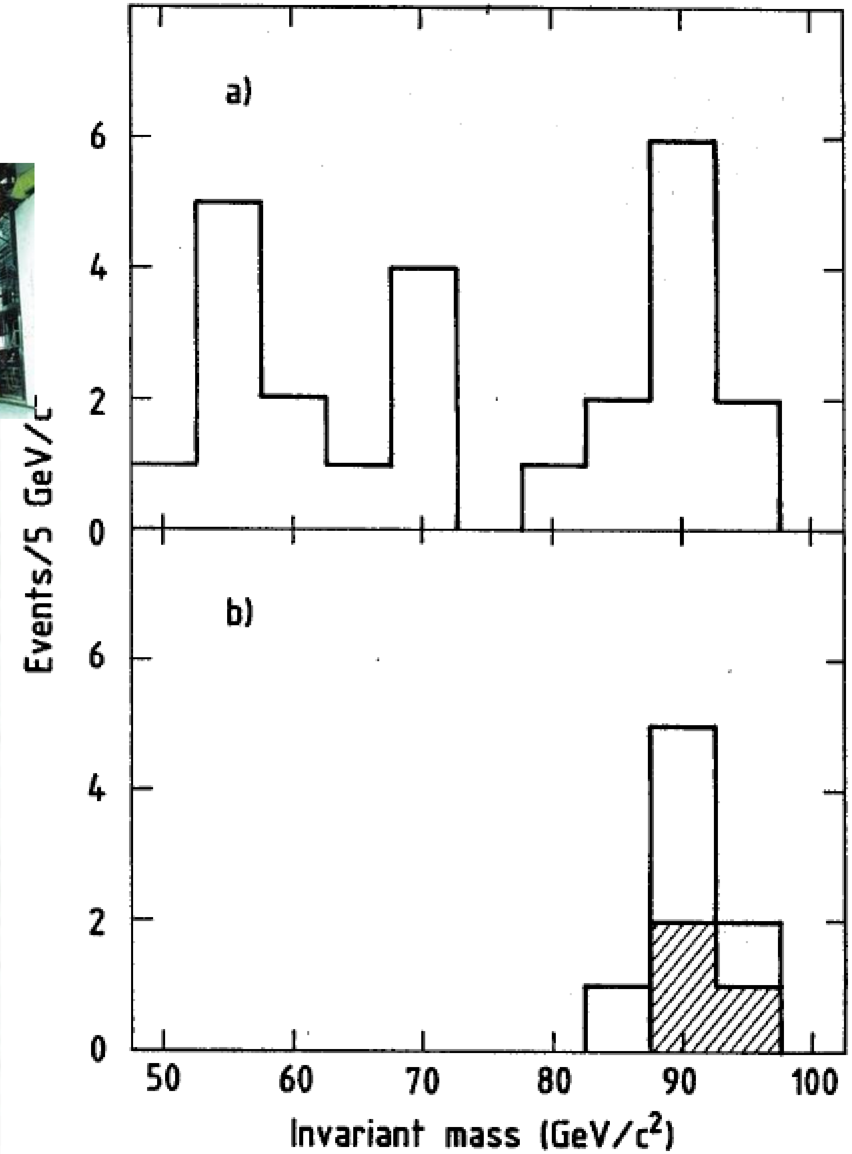
Entdeckung des Z Bosons

CERN-EP/83-112
August 11th 1983

EVIDENCE FOR $Z^0 \rightarrow e^+e^-$ AT THE CERN $\bar{p}p$ COLLIDER

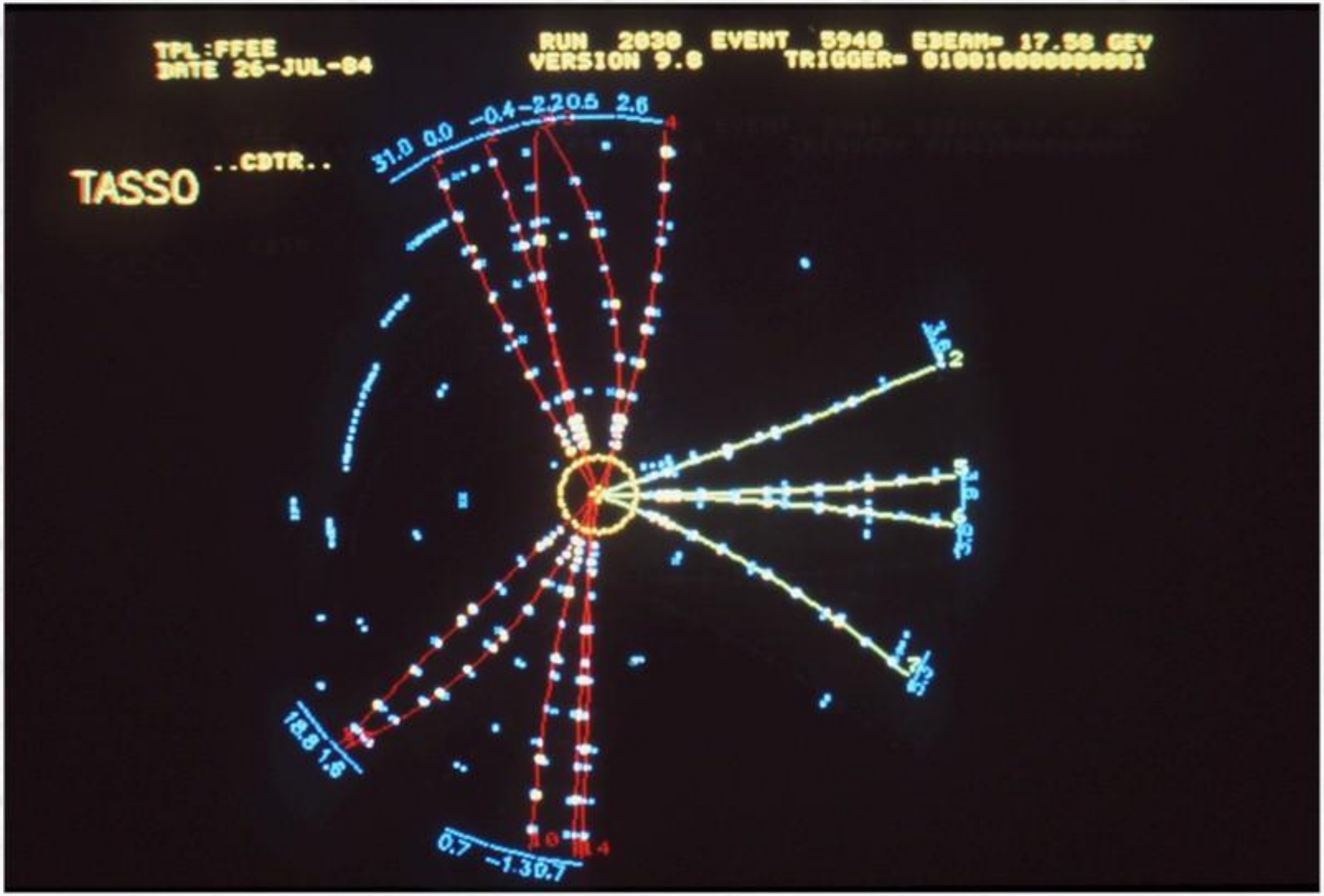
The UA2 Collaboration



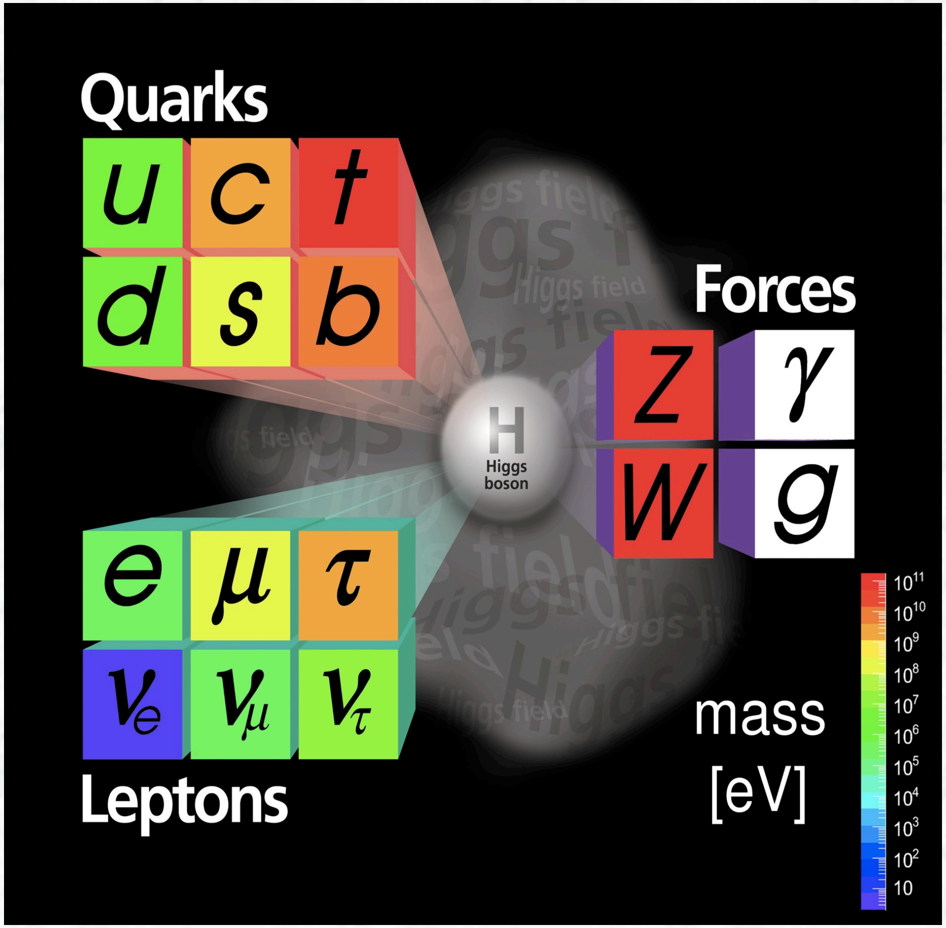


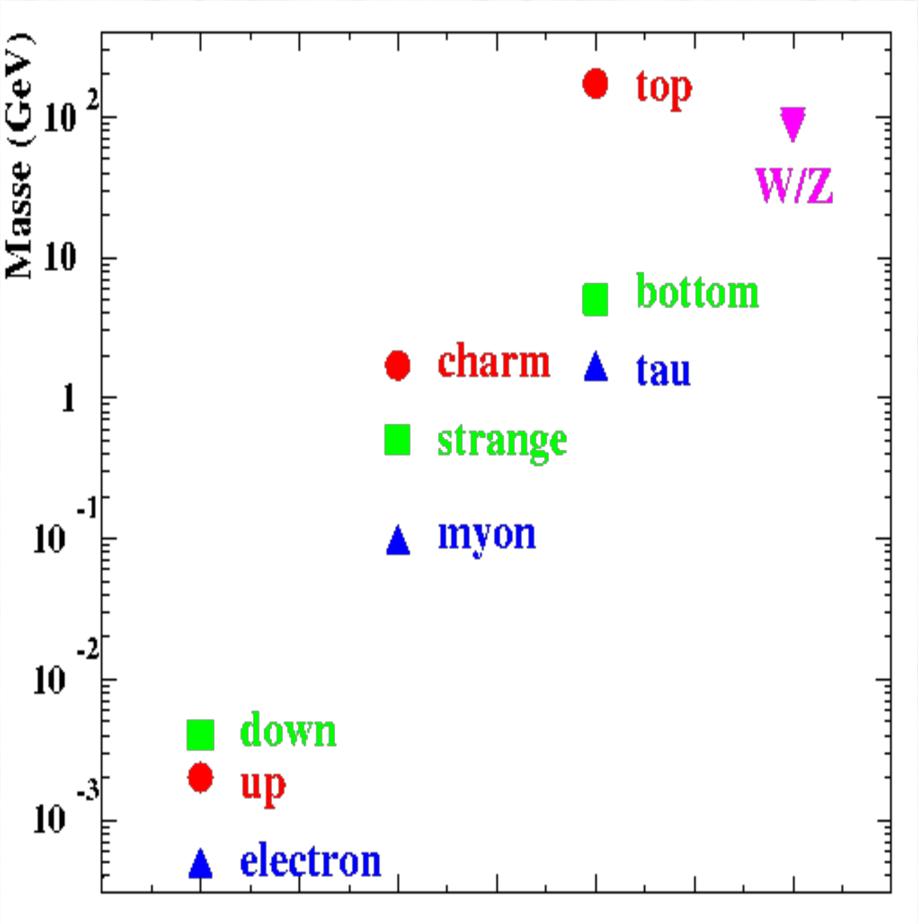
$$M_Z = 91.9 \pm 1.3 \pm 1.4 \text{ GeV}/c^2$$

Entdeckung des Gluons 1979 bei DESY



Spektrum elementarer Teilchen





Übersicht über die Kräfte

Interaction	Range	Typical Lifetime (sec)	Typical Cross Section (mb)	Typical Coupling α_i
Strong	$1\ \mathrm{F} \simeq \frac{1}{m_\pi}$	10^{-23}	10	1
	Color confinement range[a]	e.g., $\Delta \to p\pi$	e.g., $\pi p \to \pi p$	
Electromagnetic	∞	$10^{-20} \sim 10^{-16}$ e.g., $\pi^0 \to \gamma\gamma$ $\Sigma \to \Lambda\gamma$	10^{-3} e.g., $\gamma p \to p\pi^0$	10^{-2}
Weak	$\frac{1}{M_W}$ with	10^{-12} or longer	10^{-11}	10^{-6}
	$M_W \simeq 100 m_p$	e.g., $\Sigma^- \to n\pi^-$ $\pi^- \to \mu^- \bar{\nu}$	e.g., $\nu p \to \nu p$ $\nu p \to \mu^- p \pi^+$	

[a] "van der Waals" manifestation of massless gluon exchange (see end of Section 1.5).