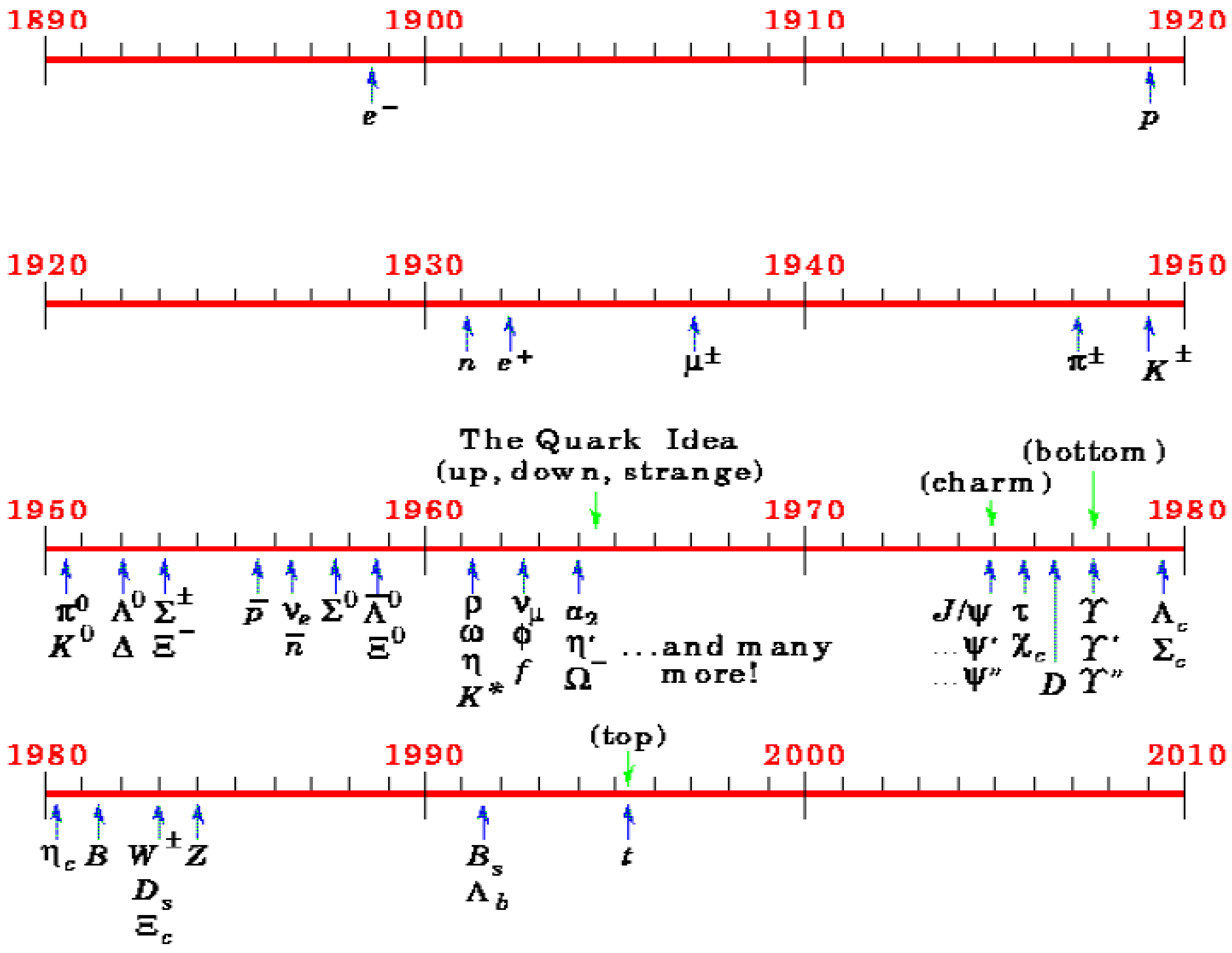
Experimentalphysik VI
Kern- und Teilchenphysik

Prof. Markus Schumacher

ALU Freiburg, Sommersemsester 2010

Kapitel 4: Grundlegende Konzepte der Teilchenphysik

Übersicht Teilchenentdeckungen



Entdeckung von Pion und Myon

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

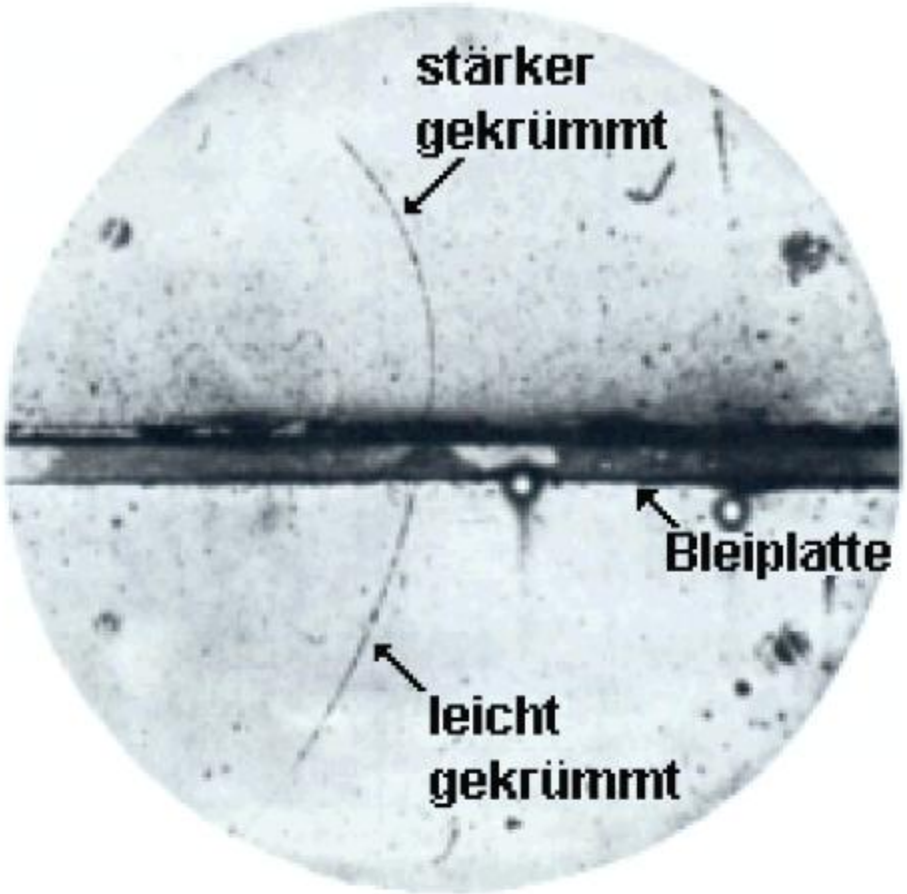
$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e} + \nu_{\mu}$

Entdeckungs 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 = ½ ħ, stabil (im Vakuum), $\tau = \infty$



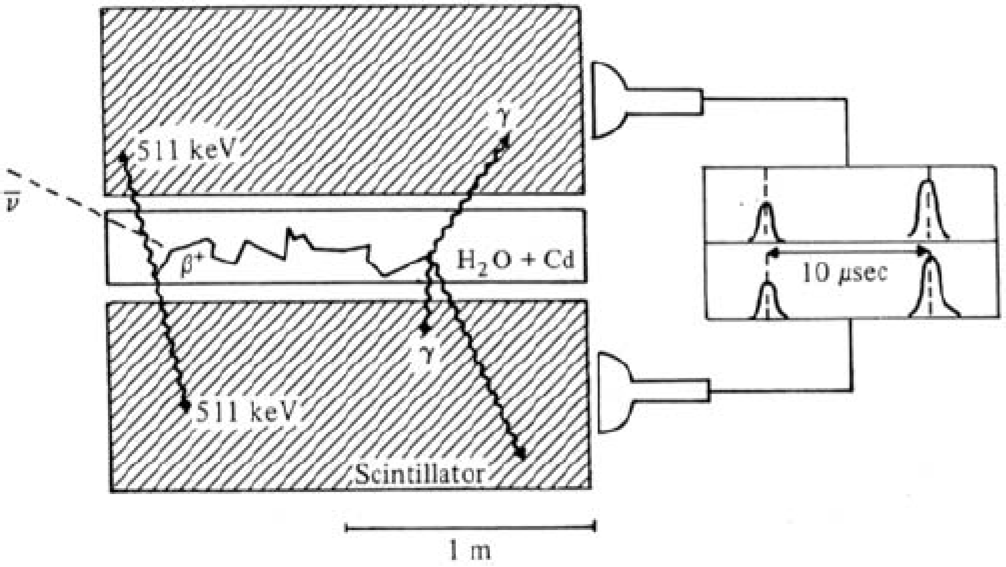
Nachweis des Elektron-Neutrinos

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

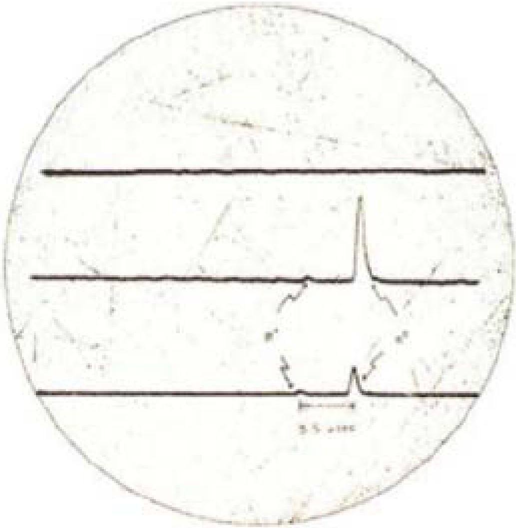
Abstand zum Detektor: 11 m, Neutrinofluss: $5 \cdot 10^{13}$ cm^{-2} sec^{-1}

Detektor: Flüssigszintillator mit Photomultiplier

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

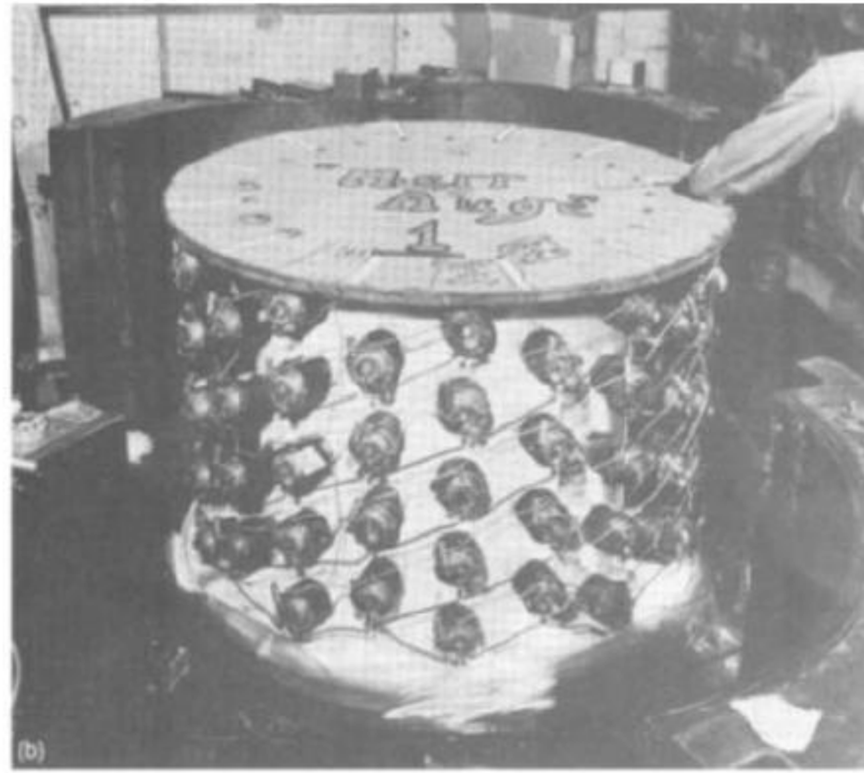


Das erste Neutrinosignal



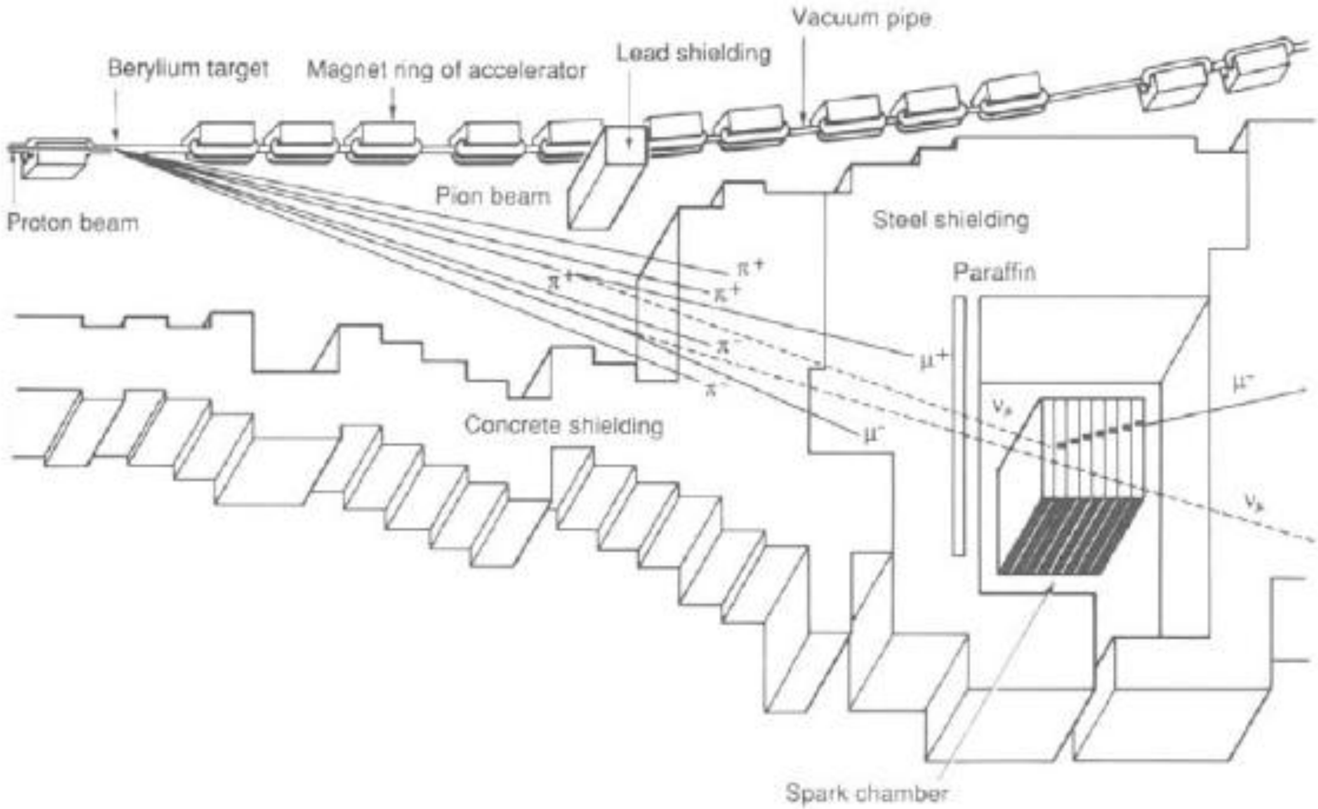
Nachweis des Elektron-Neutrinos

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)

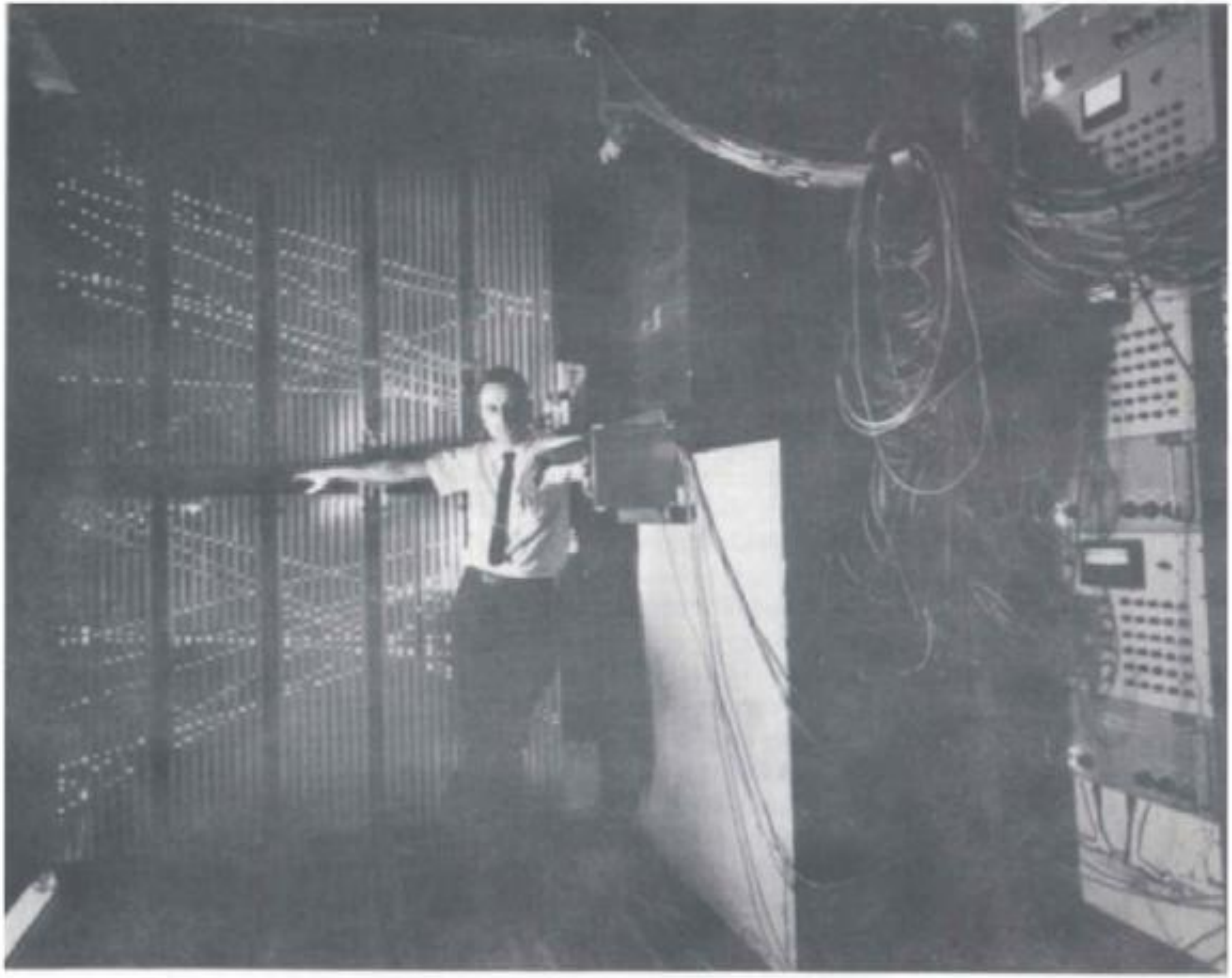
Nachweis: Myonneutrino <> Elektroneutrino



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.

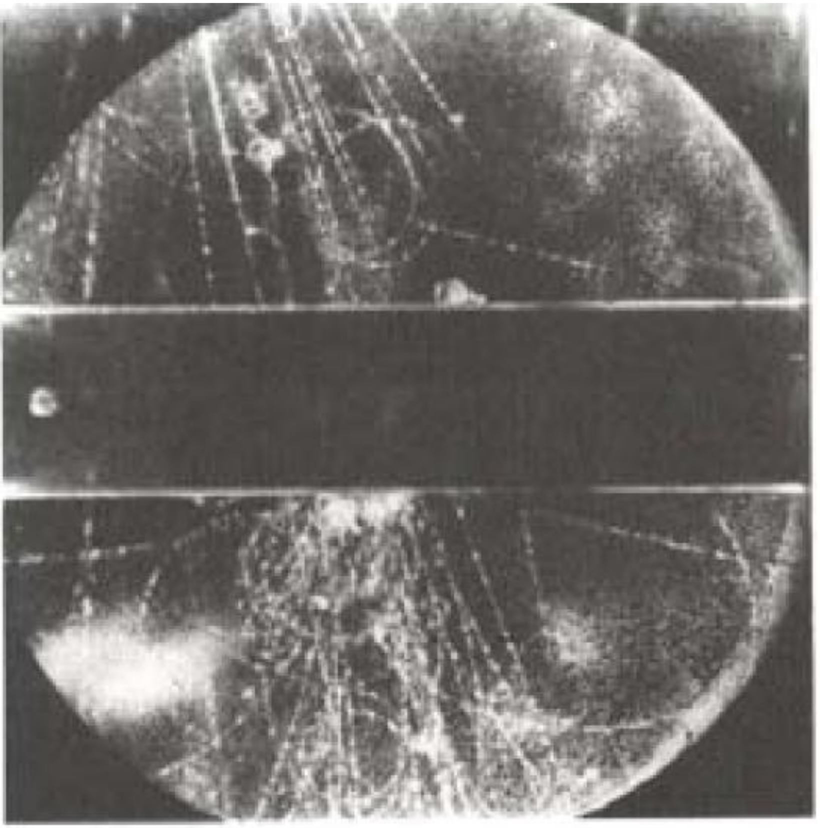
Steinberger (links),
Ledermann (2ter von rechts),
Schwartz (rechts) et al.

Nachweis: Myonneutrino <> Elektroneutrino



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.)

Entdeckung von seltsamen Teilchen: K0→π+π-



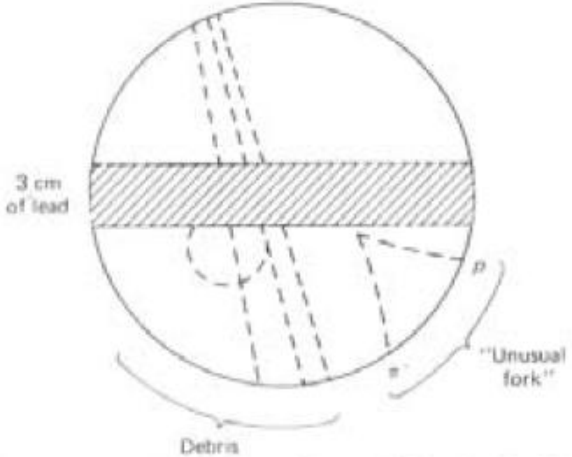
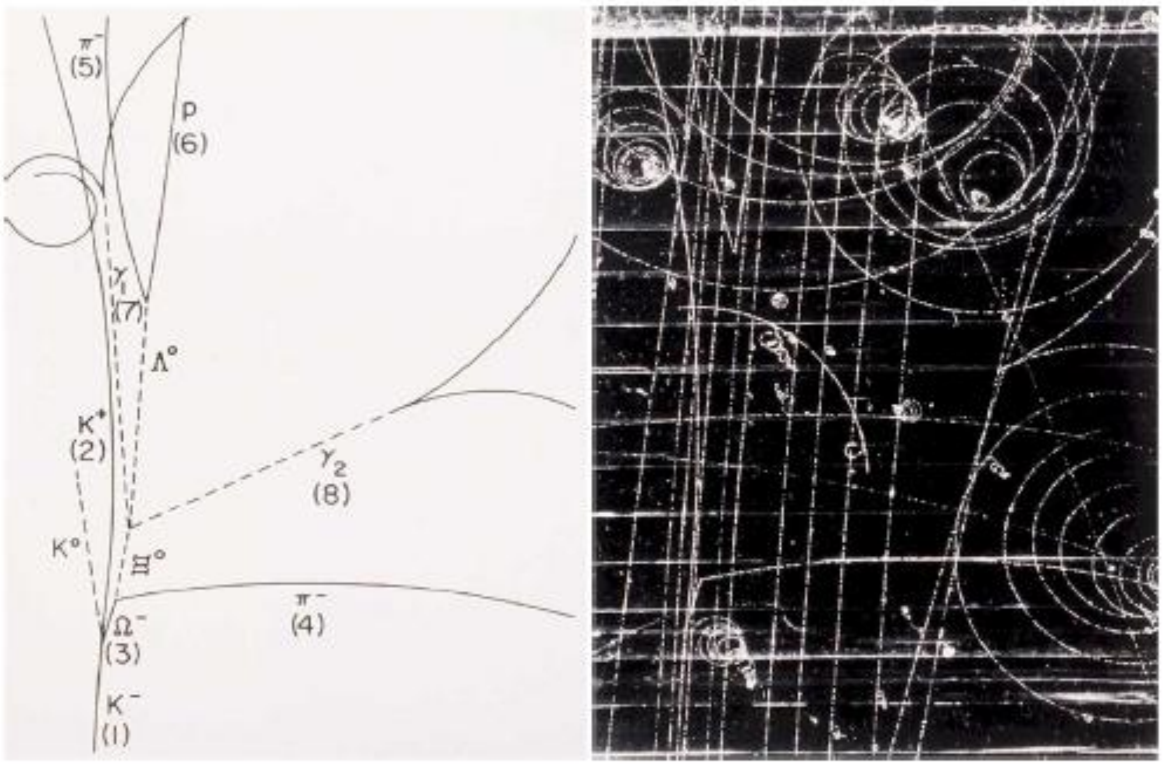


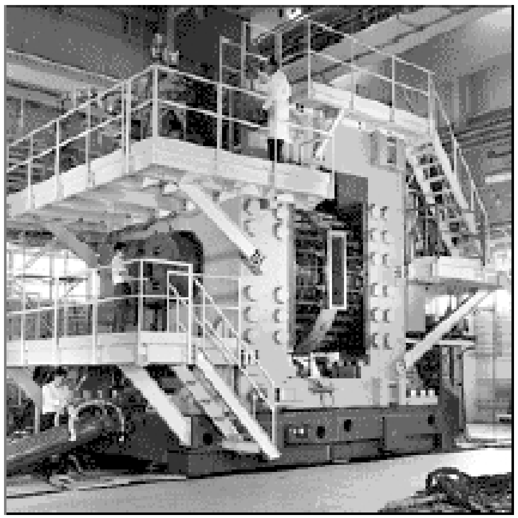
Figure 1.8 The first strange particle. Cosmic rays strike a lead plate, producing a K^0, which subsequently decays into a pair of charged pions. (Photo courtesy of Prof. G. D. Rochester. Reprinted by permission from *Nature* **160**, 855. Copyright © 1947, Macmillan Journals Limited.)

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

Übersicht Baryonen

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}	ΛK^-, $\Xi^0\pi^-$, $\Xi^-\pi^0$

Übersicht Mesonen

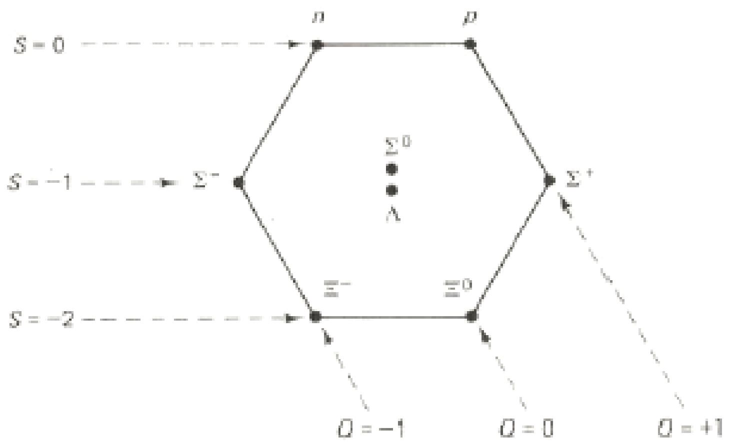
PSEUDOSCALAR MESONS (Spin 0)

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}	$\mu\nu_\mu$, $\pi^\pm\pi^0$, $\pi^\pm\pi^+\pi^-$
K^0, $\bar{K}^0$	$d\bar{s}$, $s\bar{d}$	0, 0	497.72	K_S^0 0.892×10^{-10} K_L^0 5.18×10^{-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} (for $B^\pm$, B^0)	$D + ?$
B^0, $\bar{B}^0$	$d\bar{b}$, $b\bar{d}$	0, 0	5275		
η_c	$c\bar{c}$	0	2981	6×10^{-23}	$KK\pi$, $\eta\pi\pi$, $\eta'\pi\pi$

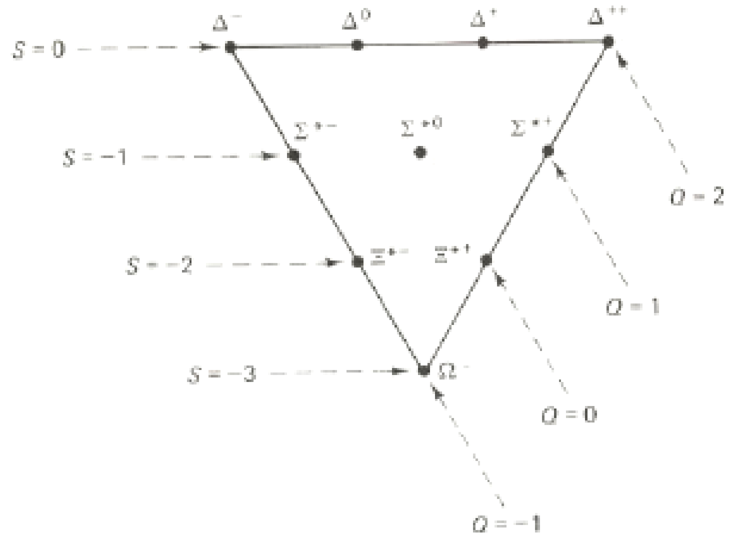
VECTOR MESONS (Spin 1)

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^-, $\mu^+\mu^-$, 5π, 7π
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^-

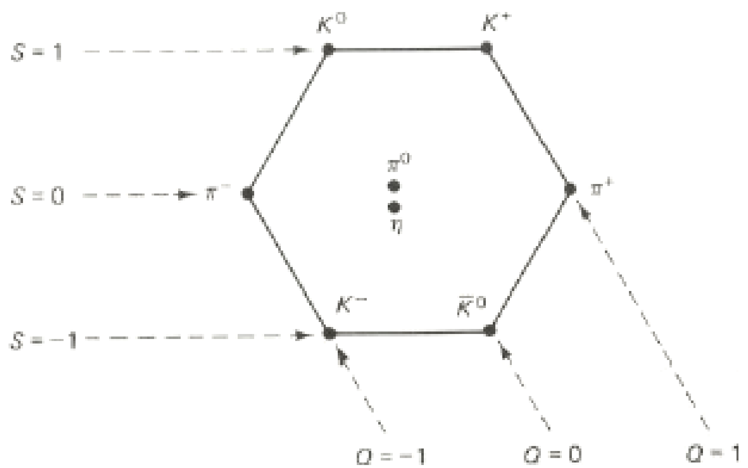
Hadronmultipletts



Das Baryonen-Oktett



Das Baryonen-Dekuplett



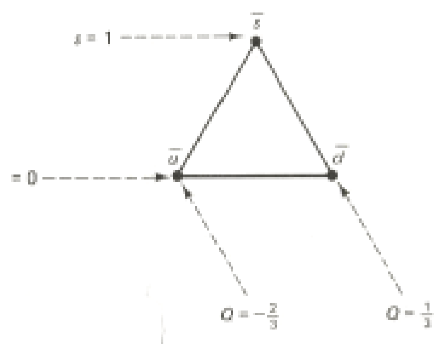
Das Mesonen-Oktett

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	??

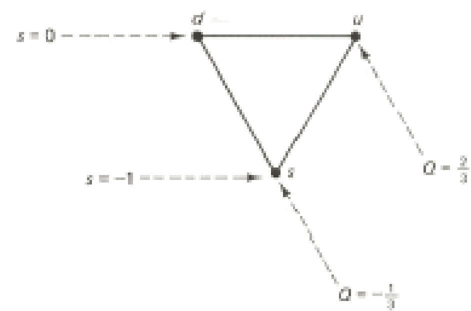
THE BARYON DECUPLET

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



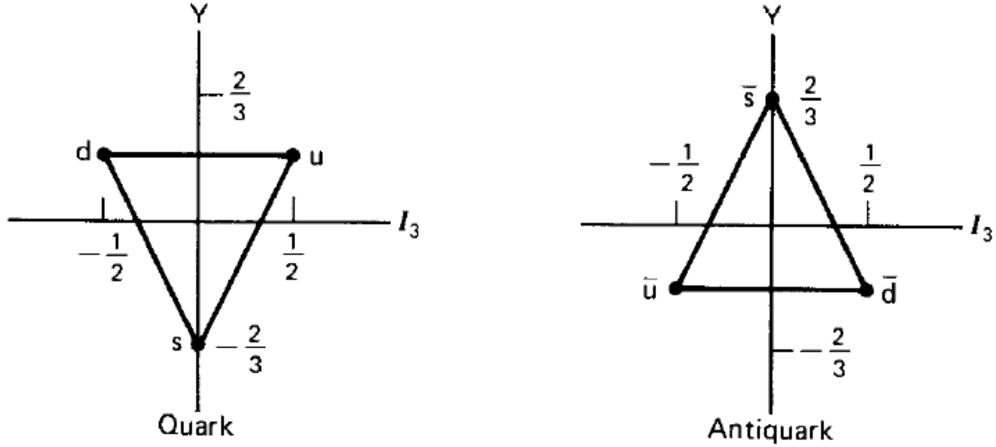


Fig. 2.4 $SU(3)$ quark and antiquark multiplets; $Y \equiv B + S$.

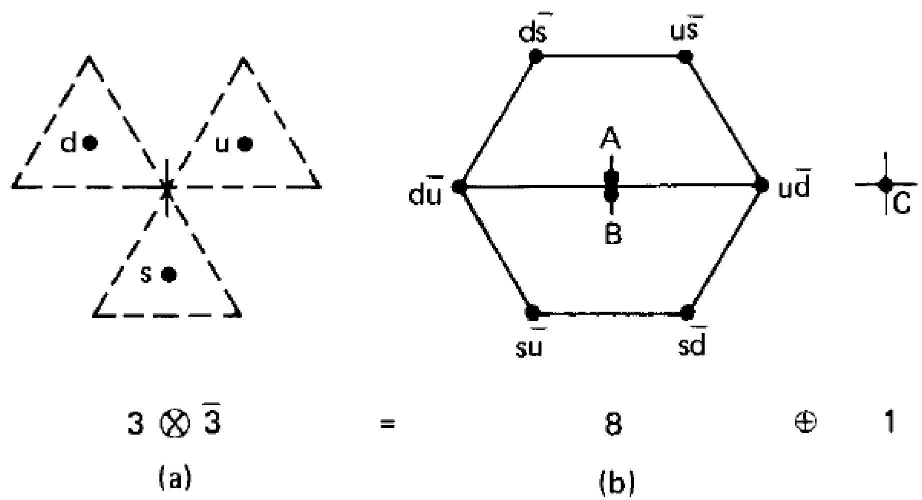


Fig. 2.5 The quark content of the meson nonet, showing the $SU(3)$ decomposition in the I_3, Y plane.

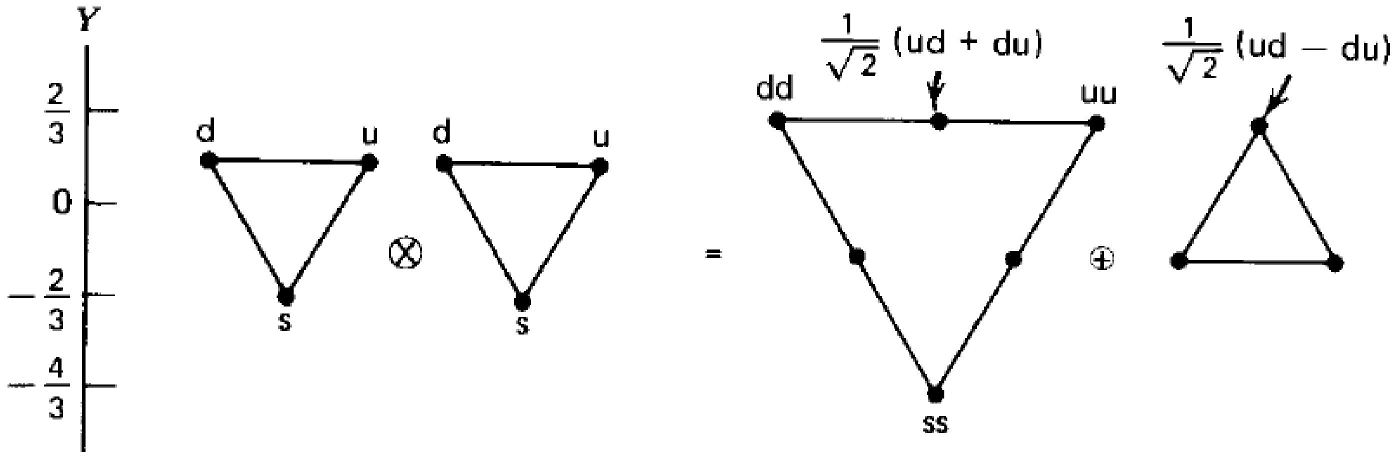


Fig. 2.6 The qq $SU(3)$ multiplets; $3 \otimes 3 = 6 \oplus \bar{3}$.

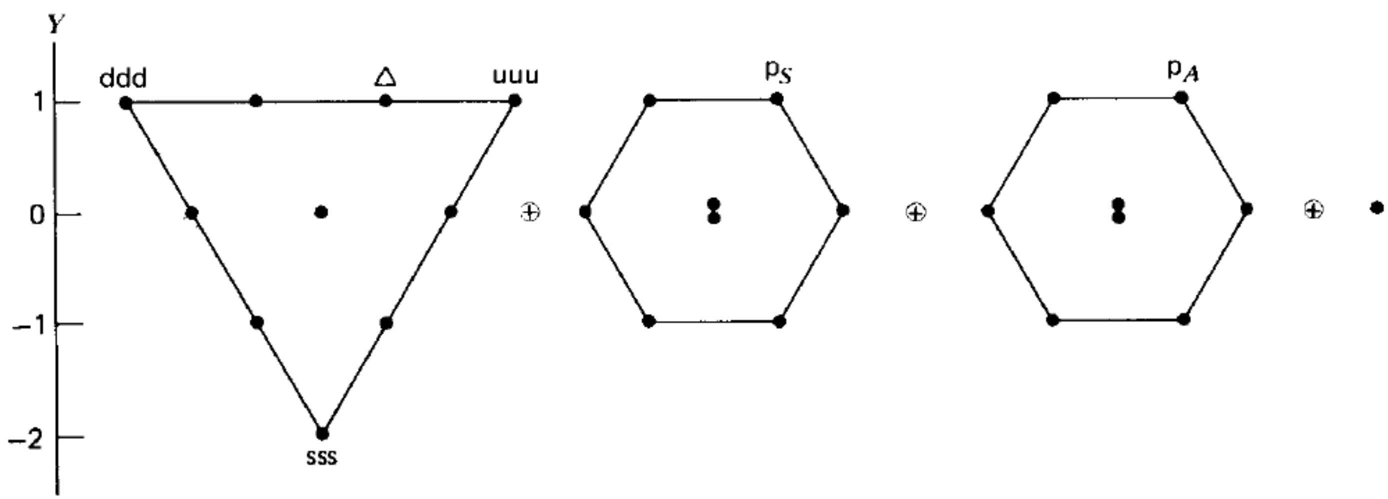


Fig. 2.7 The qqq $SU(3)$ multiplets; $3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$.

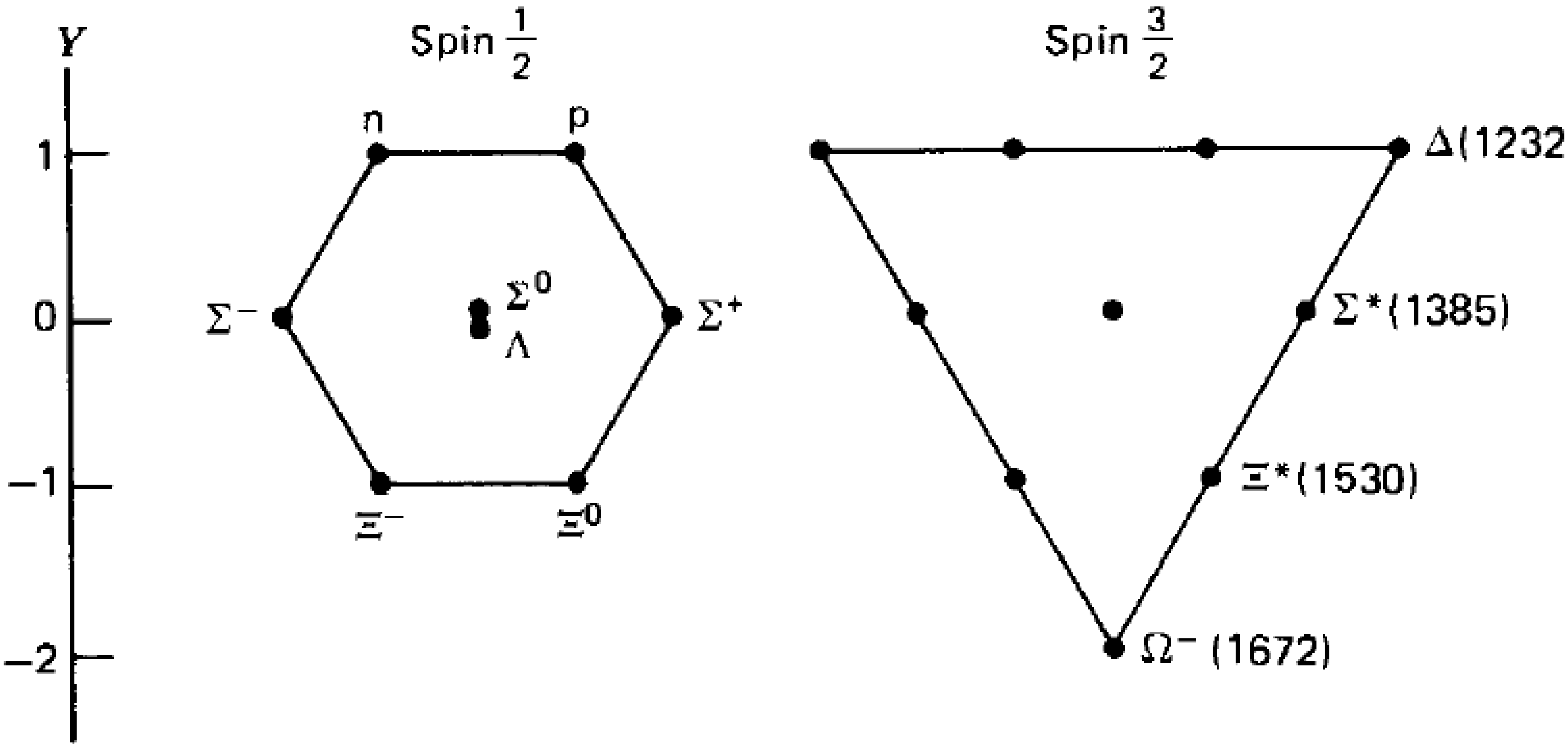


Fig. 2.8 Ground-state baryons: (8, 2) + (10, 4).

Entdeckung des J/Psi

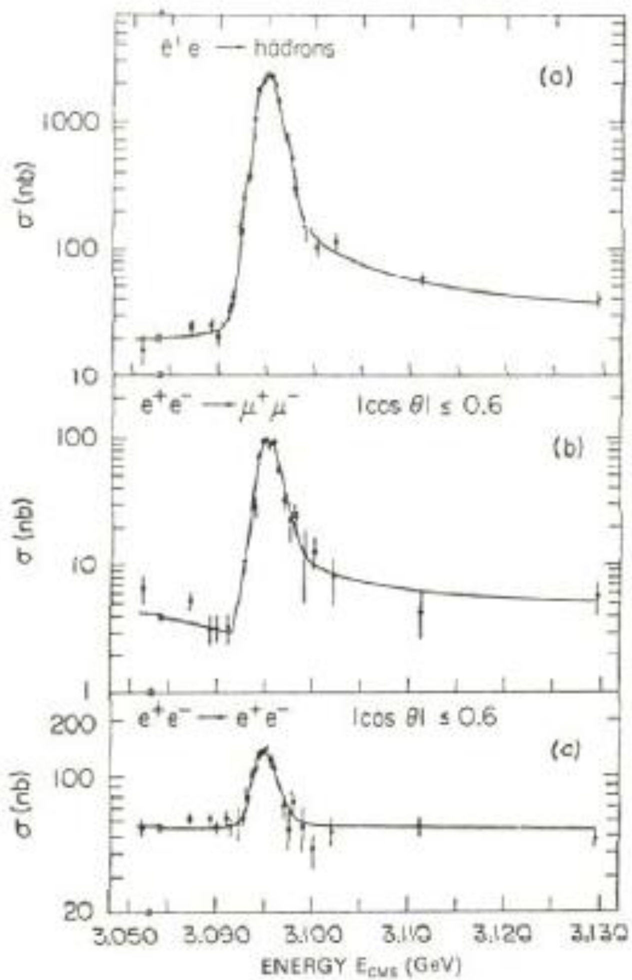


Fig. 5.10 Results of Augustin *et al.* (1974) showing the observation of the ψ/J resonance at mass 3.1 GeV, produced in e^+e^- annihilation at the SPEAR storage ring, SLAC.

(aus Ref. [8])

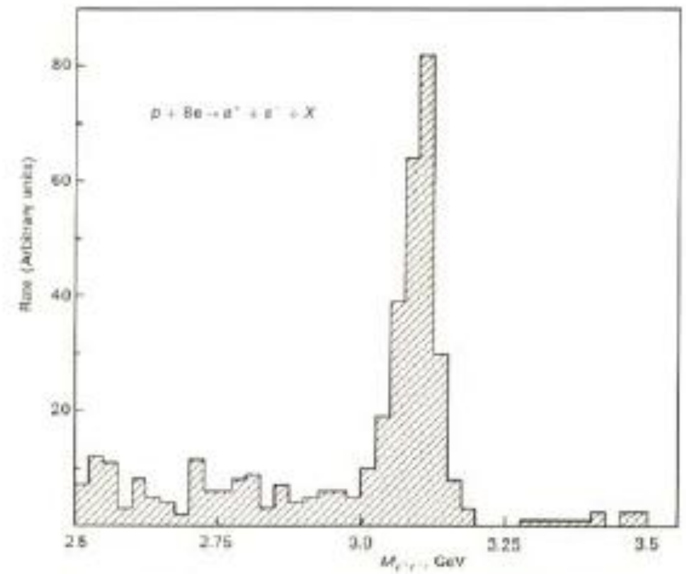
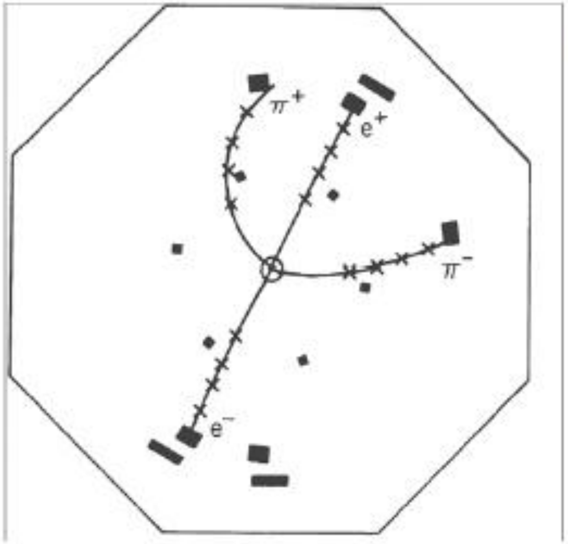


Fig. 5.11 Results of Aubert *et al.* (1974) indicating the narrow resonance ψ/J in the invariant-mass distribution of e^+e^- pairs produced in inclusive reactions of protons with a beryllium target. The experiment was carried out with the 28-GeV AGS at Brookhaven National Laboratory.

(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

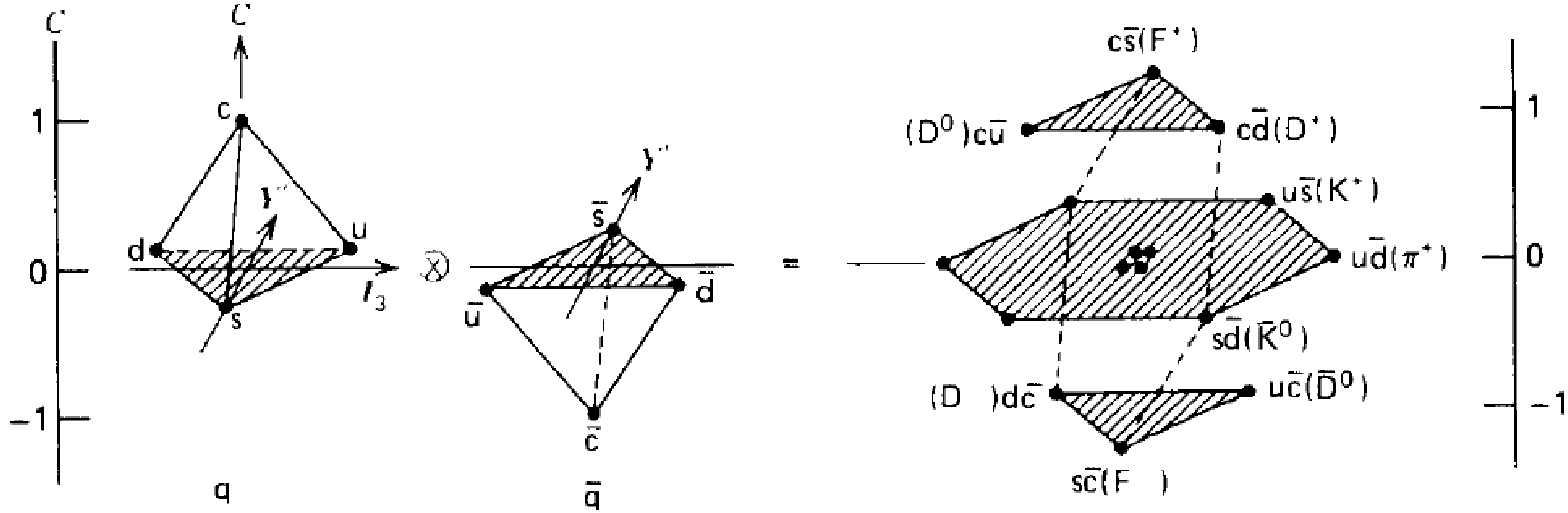
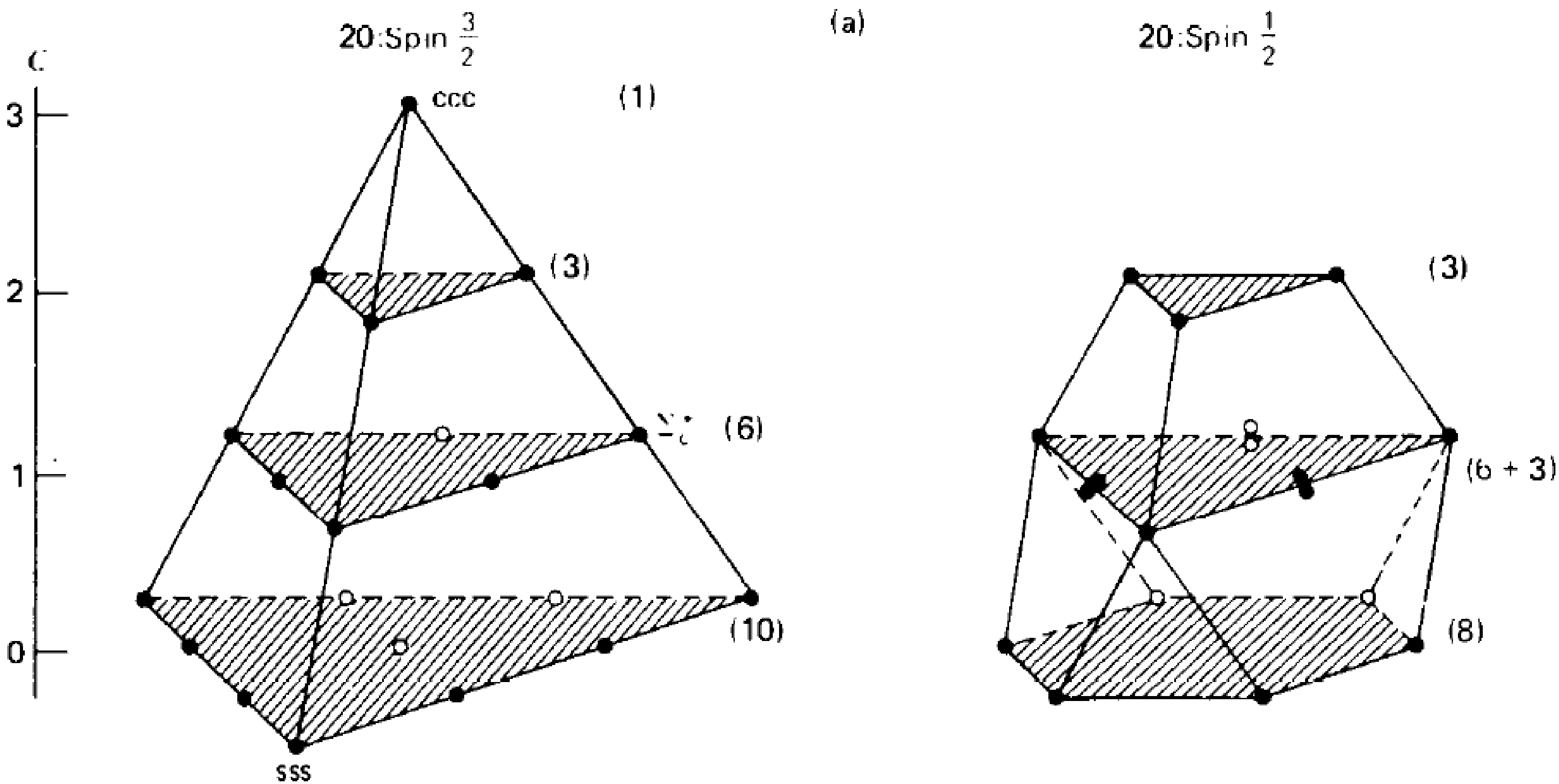


Fig. 2.12 The 16 meson states made from u, d, s, c quarks, plotted in (I_3, Y', C) space with $Y' = Y - \frac{4}{3}C$. Some members of the $J^P = 0^-$ multiplet are indicated.

Baryonen im 4-Flavour-Quark-Modell

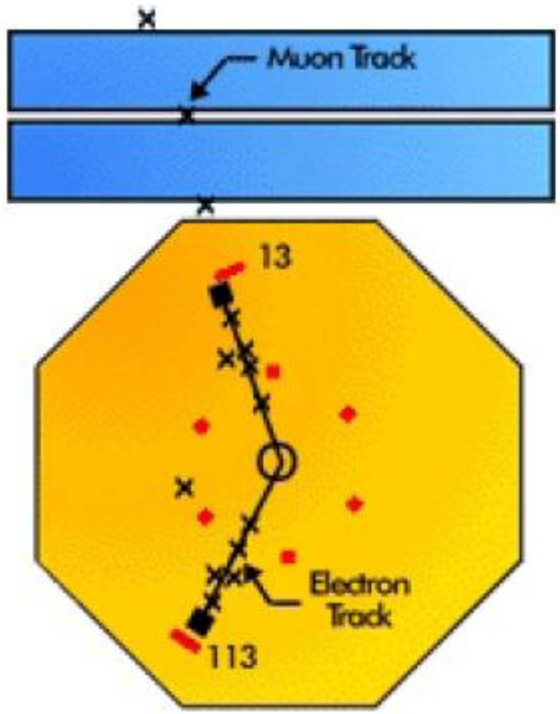


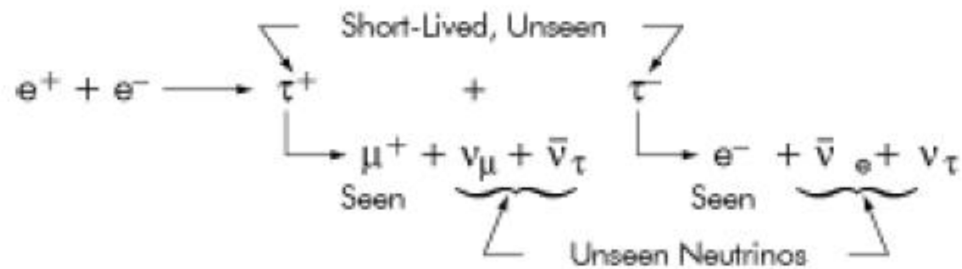
1975: Stanford Linear Accelerator Center, SLAC, M. Perl
Studium von e^+e^- Kollisionen mit dem MARK-I Detektor am Speicherring SPEAR (Strahlenergie 4 GeV)

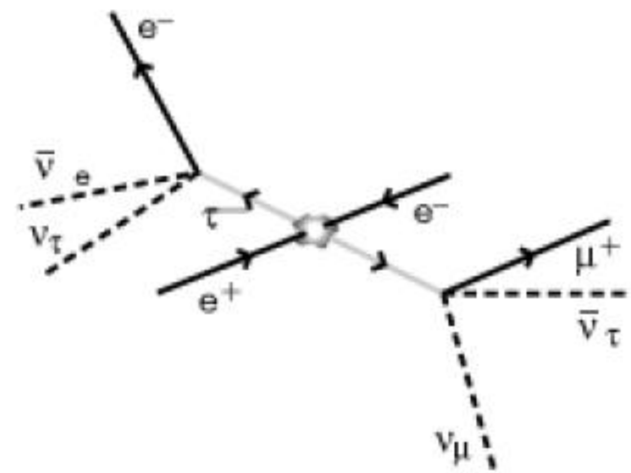
SLAC-PUB-1626
LBL-4228
August 1975
(T/E)

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

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







Entdeckung des Upsilon am Fermilab

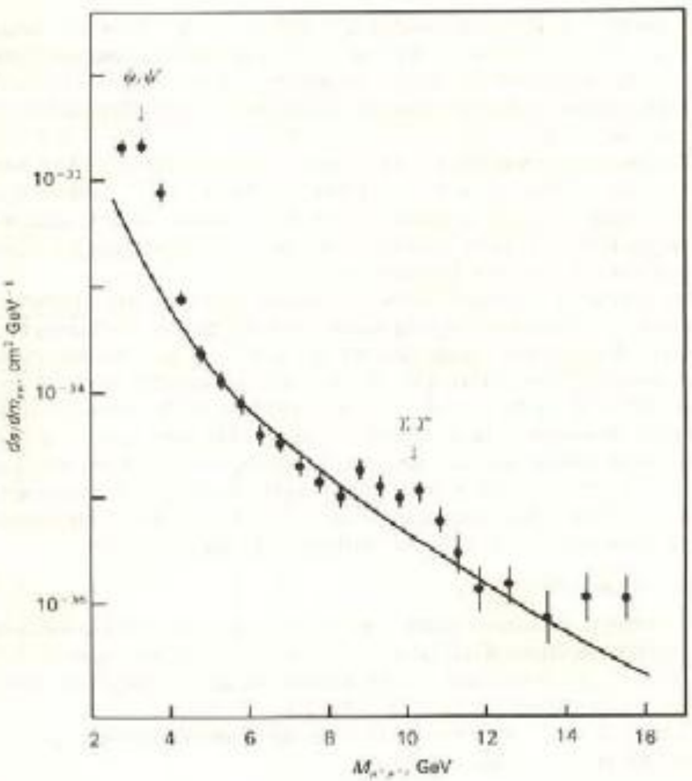


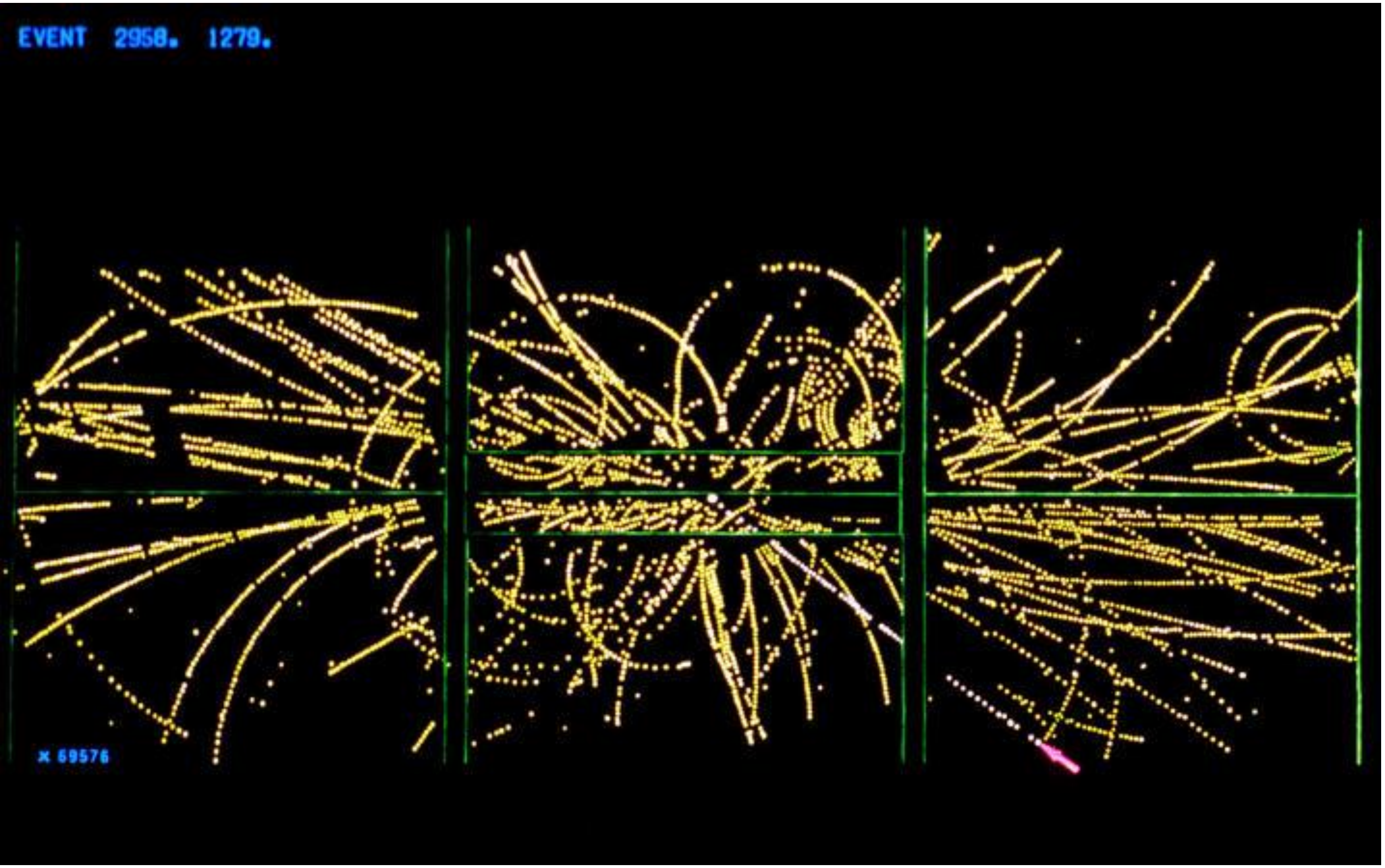
Fig. 5.16 First evidence for the upsilon resonances Υ, Υ', obtained by Herb *et al.* (1977) from the spectrum of muon pairs observed in 400-GeV proton-nucleus collisions at Fermilab, near Chicago. The enhancement due to these resonances stands out against the rapidly falling continuum background. (aus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

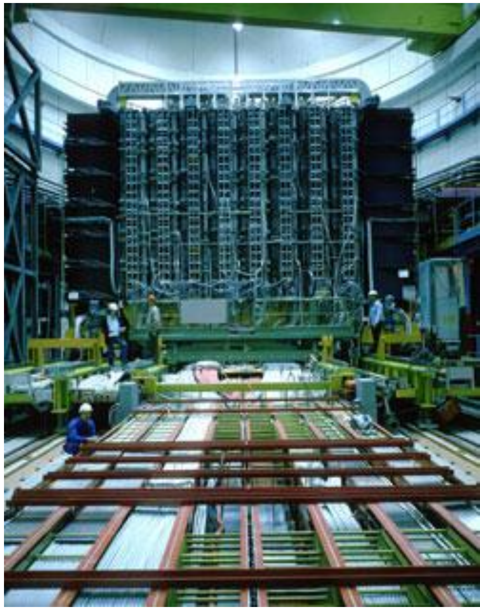
L. Ledermann et al.,
Fermilab (1977)

Entdeckung der intermedären Vectorbosonen

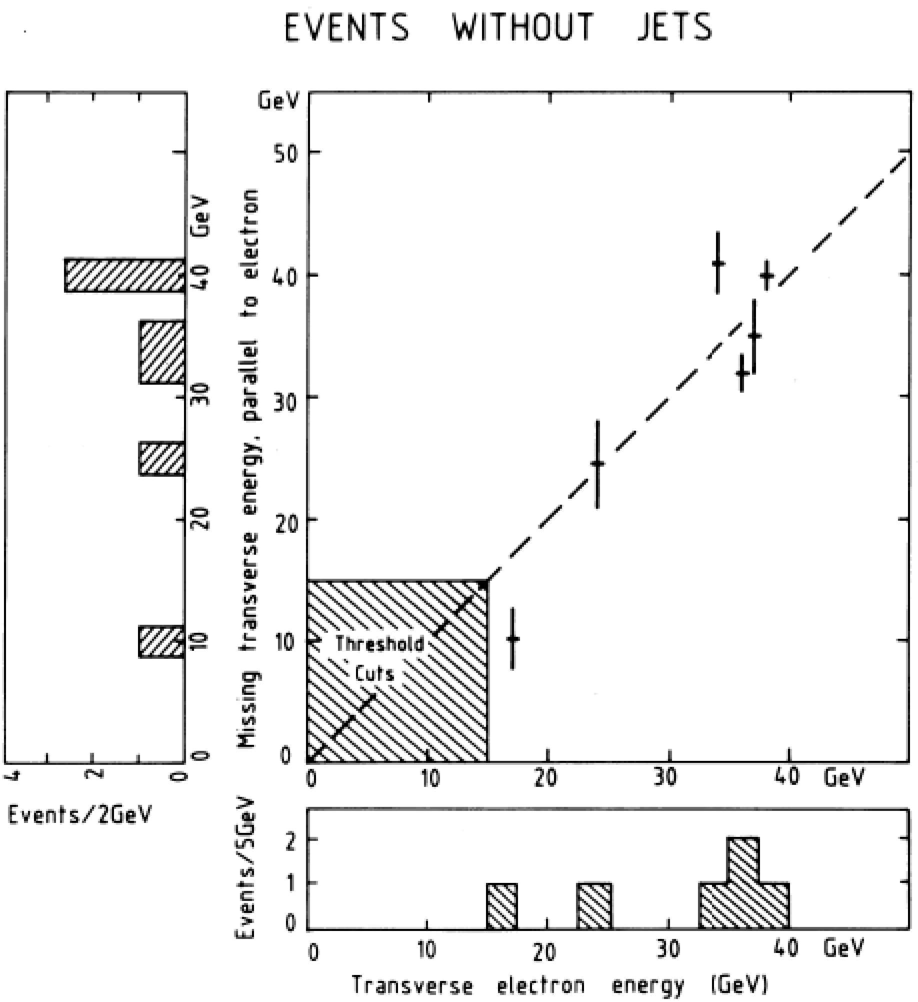
EXPERIMENTAL OBSERVATION OF ISOLATED LARGE TRANSVERSE ENERGY ELECTRONS WITH ASSOCIATED MISSING ENERGY AT $\sqrt{s}$ = 540 GeV

UA1 Collaboration, CERN, Geneva, Switzerland

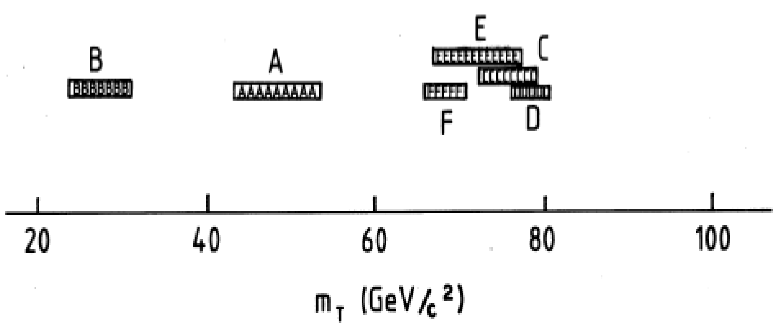




Entdeckung des W mi UA1 Am SPPS bei CERN

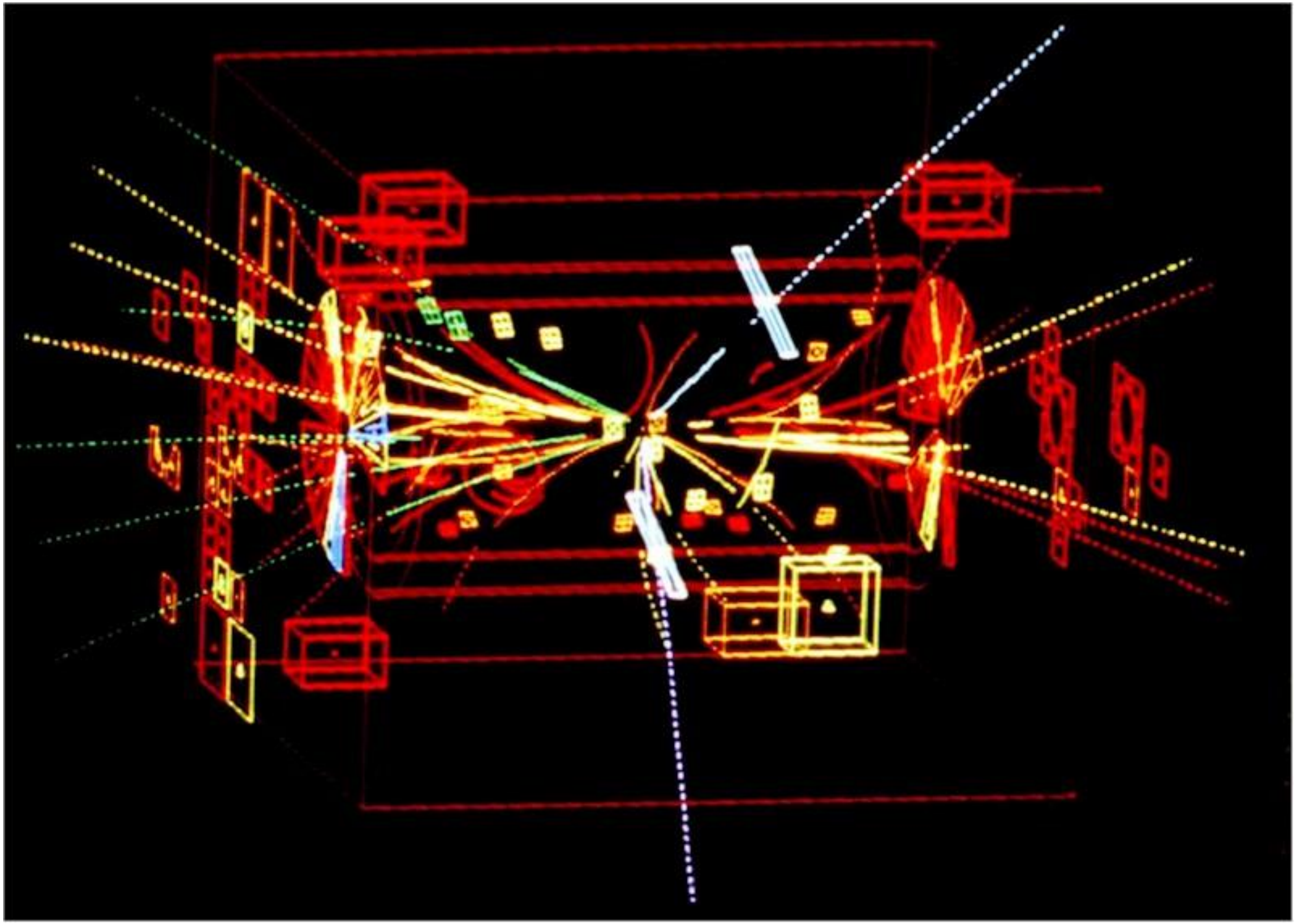


$$m_T^2 = 2p_T^{(e)} p_T^{(\nu)} (1 - \cos \phi_{\nu_e})$$



$$m_W = 81 {+5 \atop -5} \text{ GeV}/c^2$$

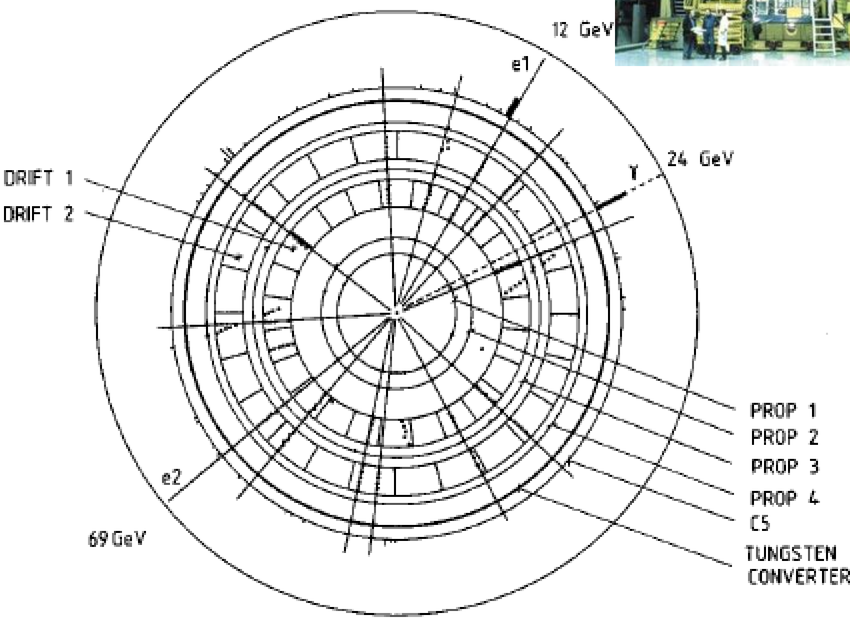
Erstes Z in UA1 am SPPS beim CERN

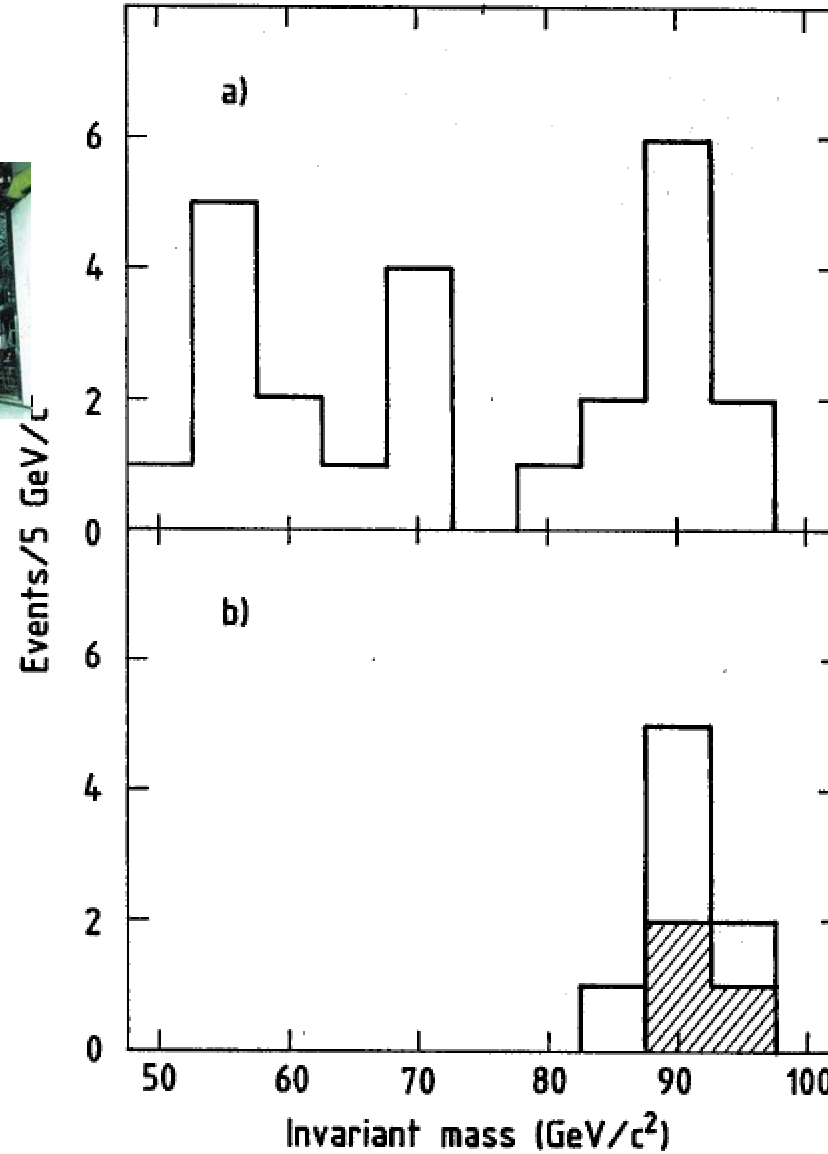


CERN-EP/83-112
August 11th 1983

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

The UA2 Collaboration





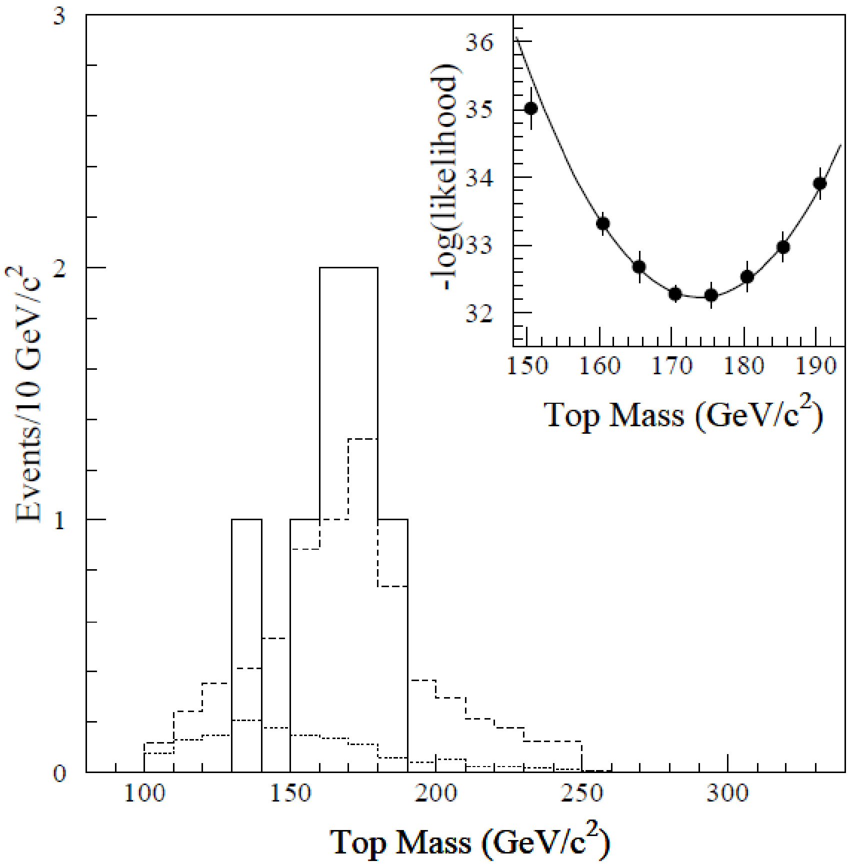
$$M_Z = 91.9 \pm 1.3 \pm 1.4 \ \mathrm{GeV}/c^2$$

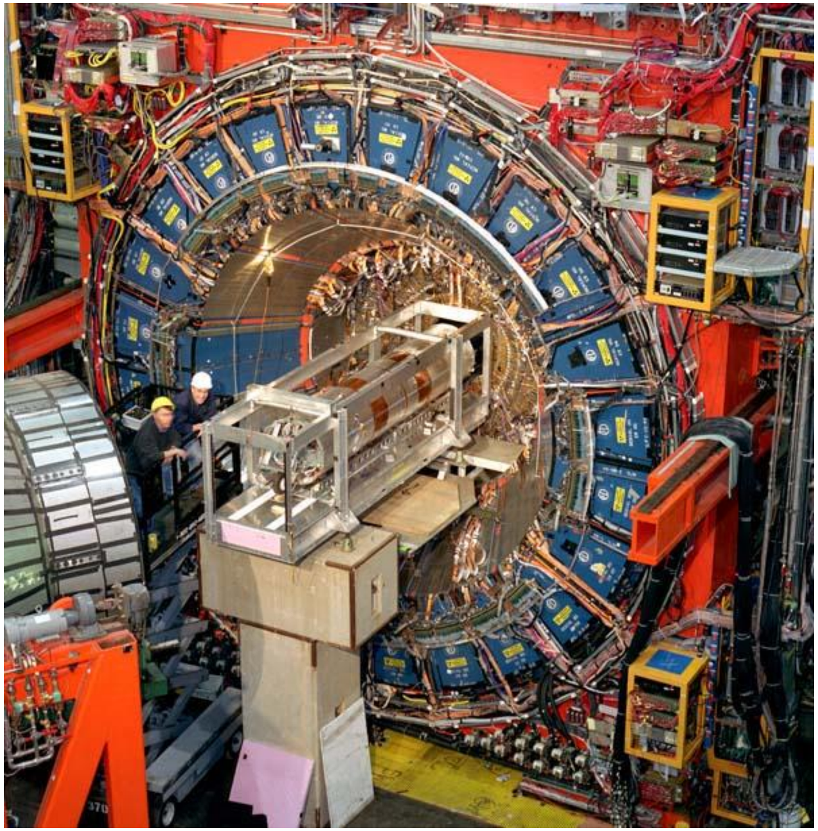
Nachweis des Gluons 1979 bei PETRA am DESY

Nachweis des Top-Quarks 1994

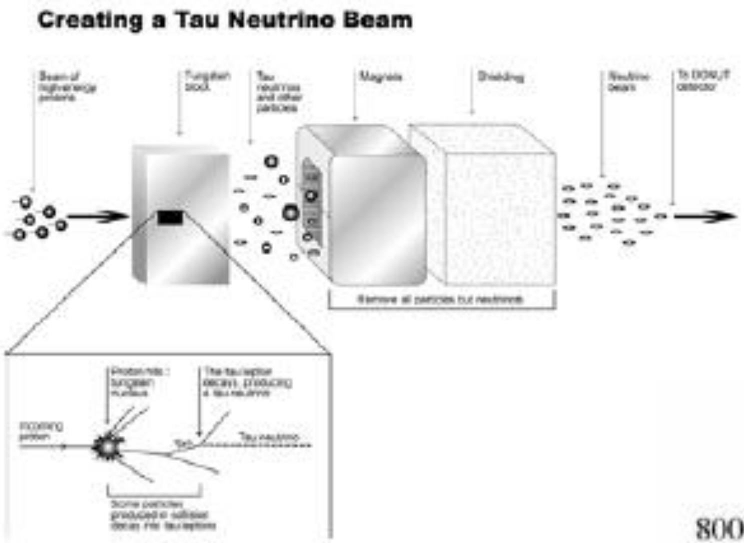
FERMILAB-PUB-94/116-E
CDF/PUB/TOP/PUBLIC/2595
May 16, 1994

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





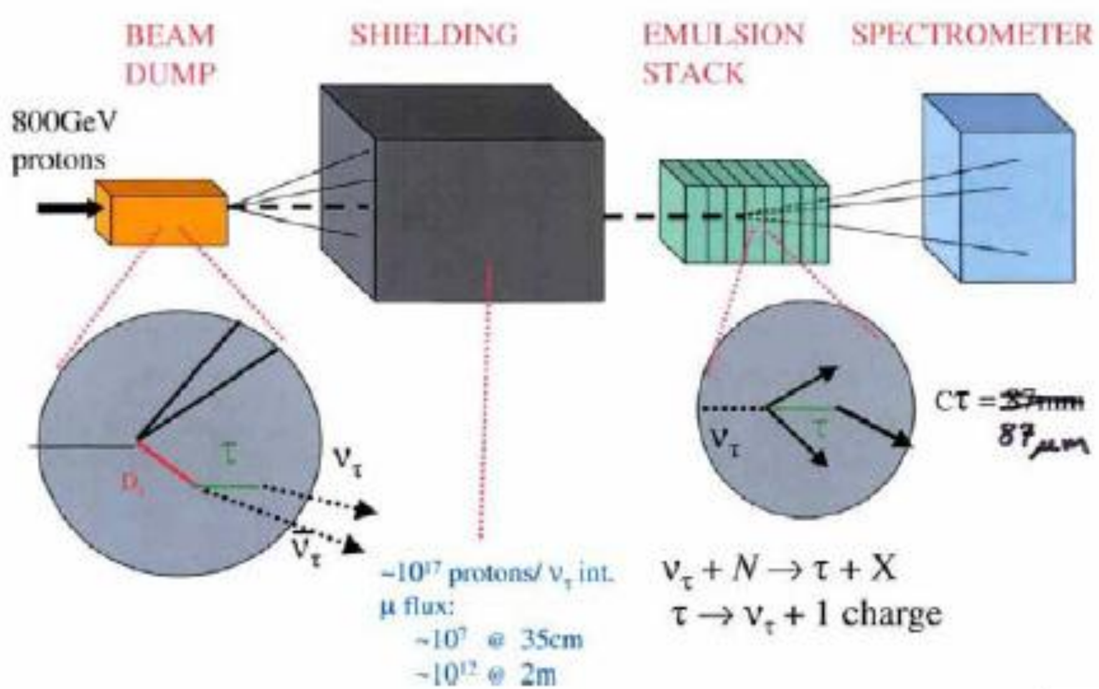
$$M_{top} = 174 \pm 10^{+13}_{-12}$$



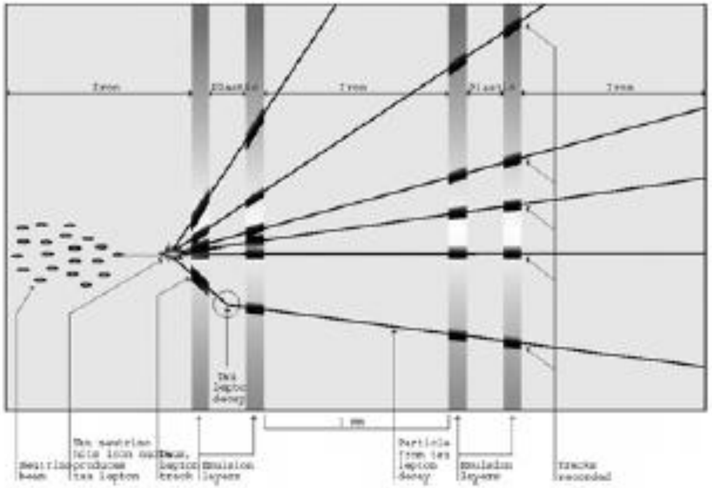
Observation of Tau Neutrino Interactions

DONUT Collaboration

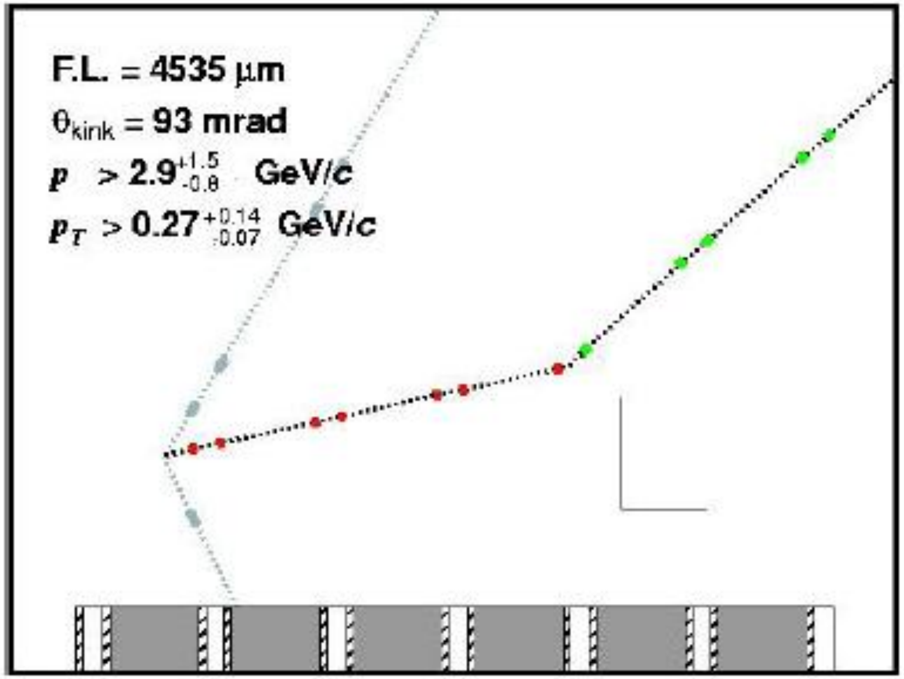
December 14, 2000



Nachweis des Tau-Neutrinos

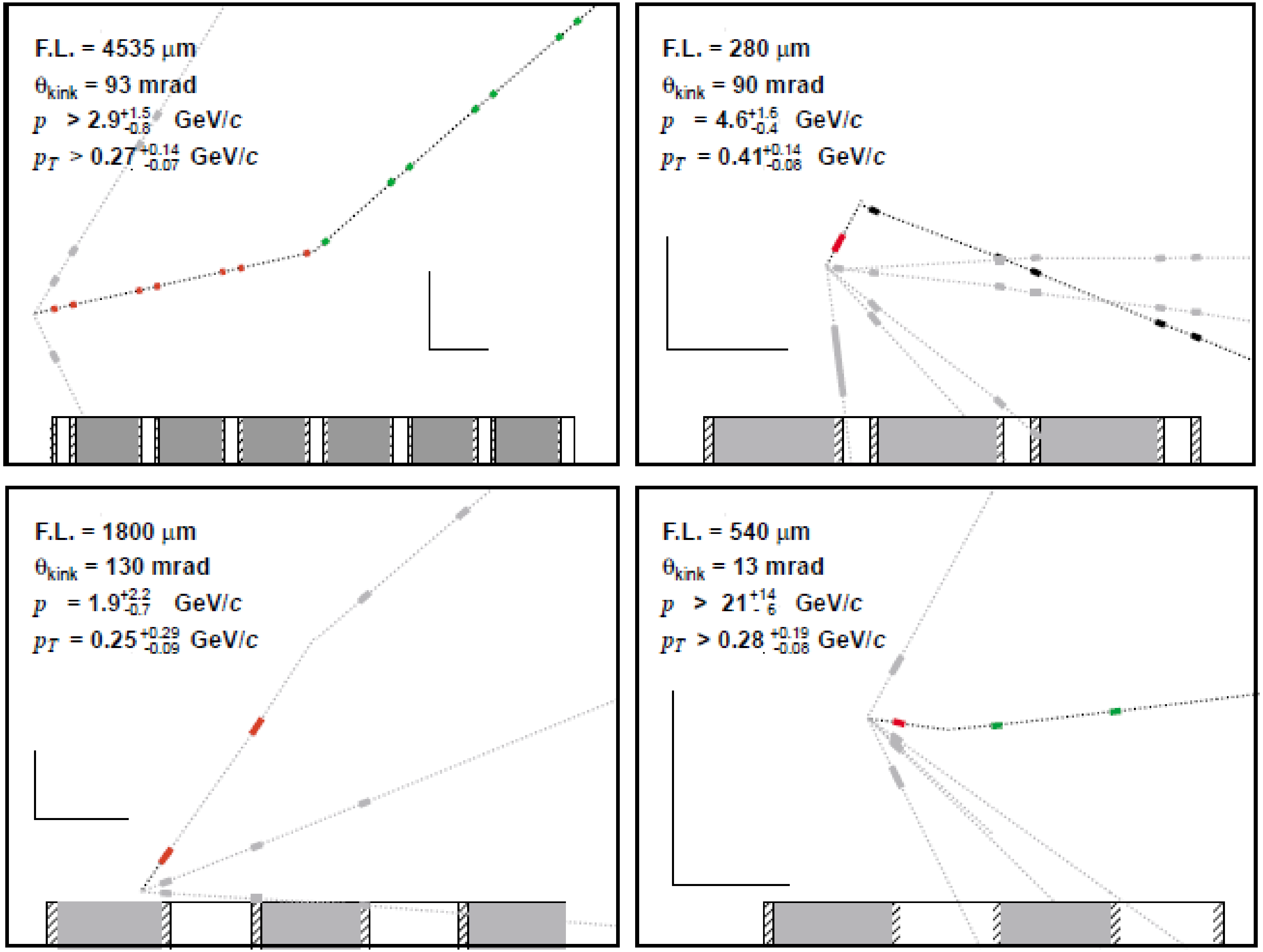


Prinzip des ν_τ Nachweises



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

Nachweis des Tau-Neutrinos



Übersicht Wechselwirkungen bzw. Kräfte

Interaction	Range	Typical Lifetime (sec)	Typical Cross Section (mb)	Typical Coupling α_i
Strong	$1\ \text{F} \simeq \frac{1}{m_\pi}$	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).