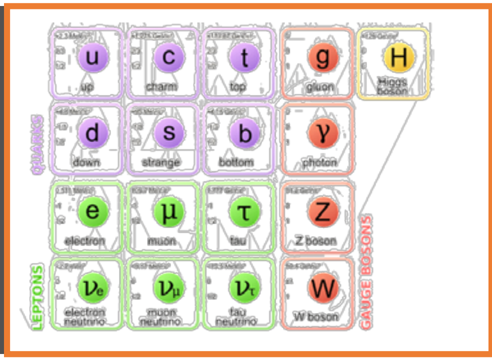
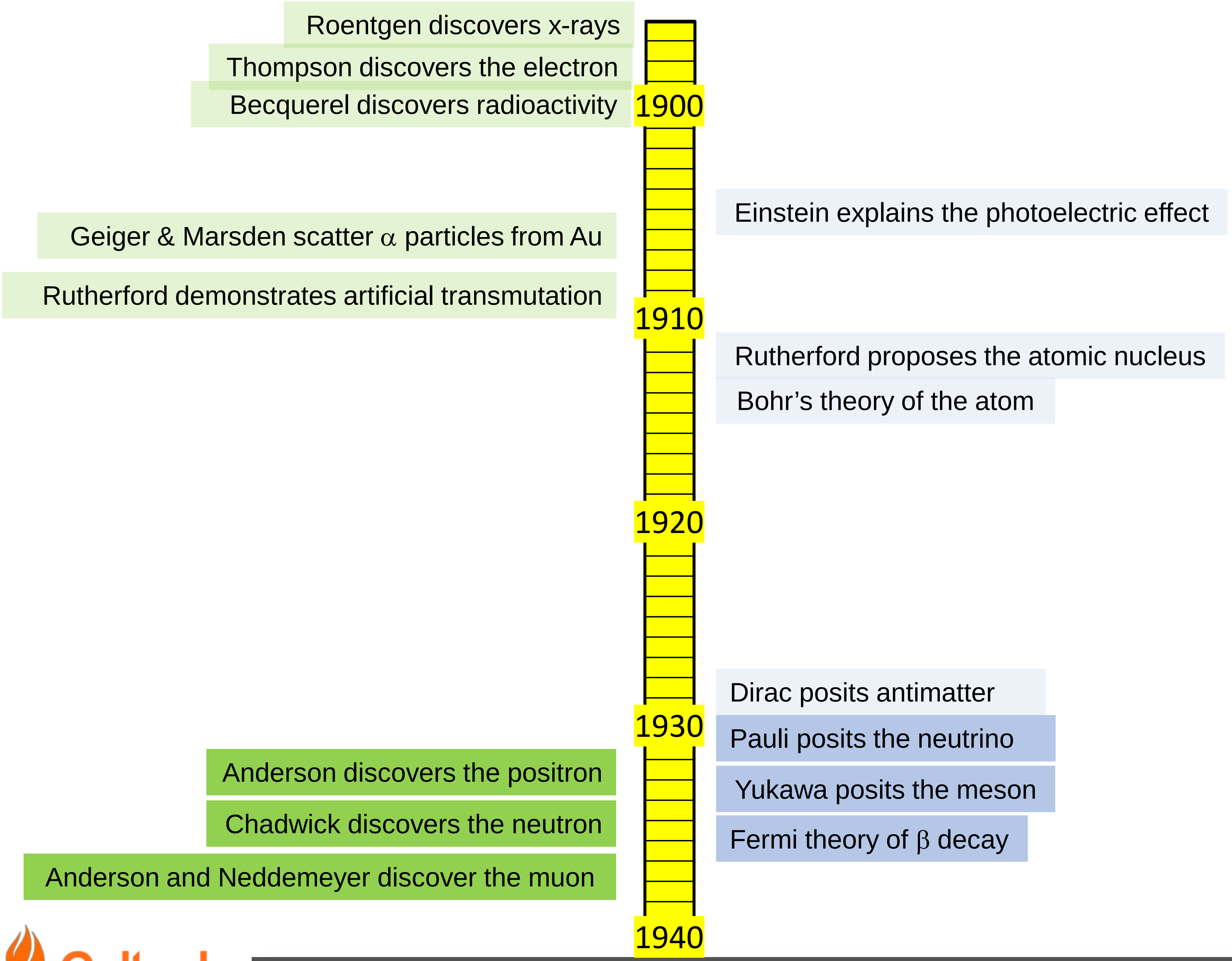
Critical Experiments: Flavor



David Hitlin
Caltech
SLAC Summer Institute
August 1, 2018

Critical Experiments (Flavor)

- I’m going to review a selection of experiments crucial to the development of the flavor sector of the Standard Model, hopefully without too much duplication of the presentations of Breidenbach, Jenni and Kearns
- The exploration of the flavor sector naturally overlaps other areas, so I won’t be able to color completely within the lines
- I’ll include a (personal) selection of the Greatest Hits, and, in addition, some items that may not be well-known, but were, in my estimation, important in determining the of the Standard Model
- By proceeding more-or-less chronologically, I hope you will appreciate that an well-ordered development process is apparent only by looking in the rear view mirror
- In organizing this talk, the first question I asked myself was “Where did flavor physics start?”



Roentgen discovers x-rays

Thompson discovers the electron

Becquerel discovers radioactivity

Einstein explains the photoelectric effect

Geiger & Marsden scatter α particles from Au

Rutherford demonstrates artificial transmutation

Rutherford proposes the atomic nucleus

Bohr’s theory of the atom

Dirac posits antimatter

Pauli posits the neutrino

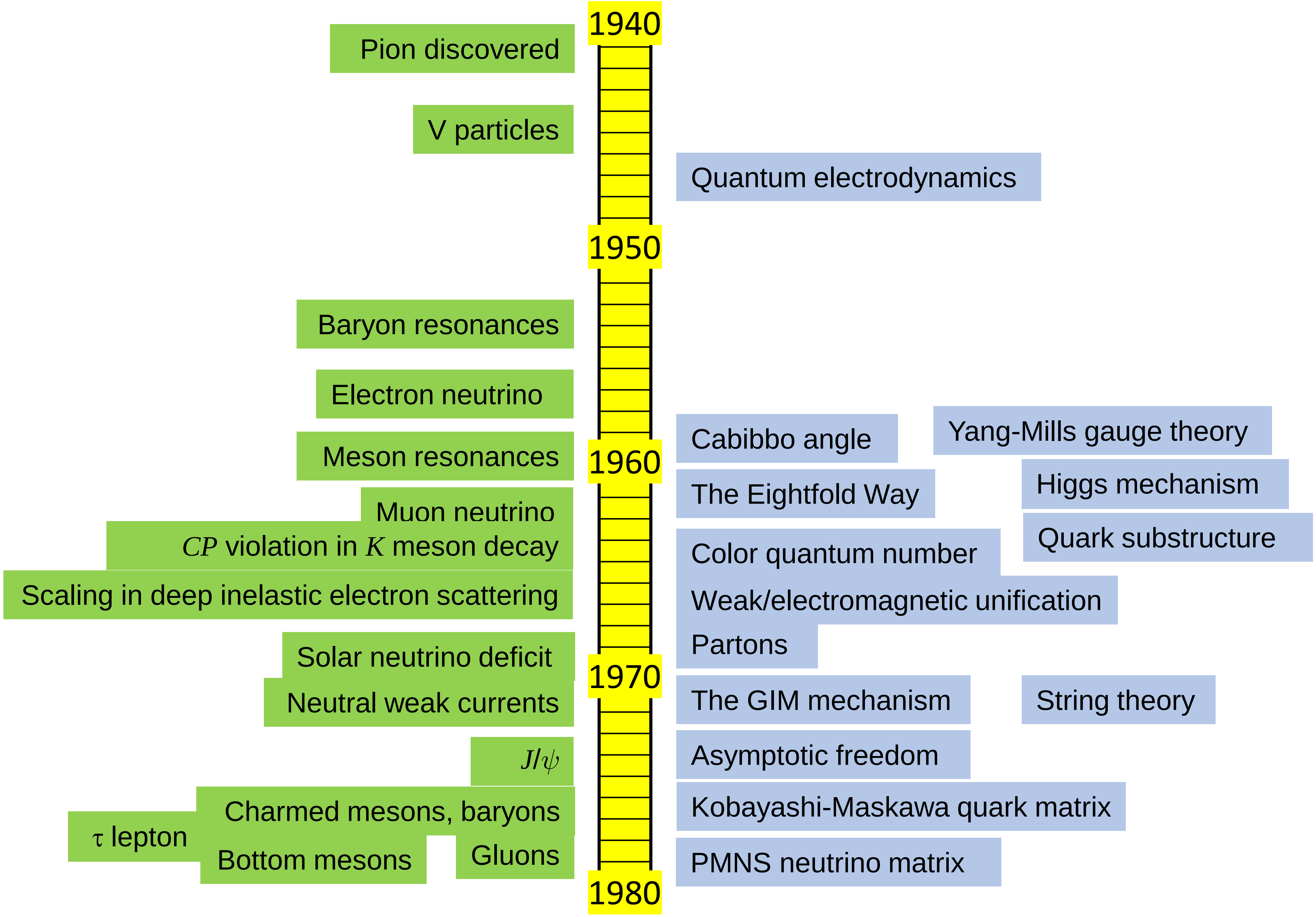
Anderson discovers the positron

Yukawa posits the meson

Chadwick discovers the neutron

Fermi theory of β decay

Anderson and Neddemeyer discover the muon



Pion discovered

V particles

Baryon resonances

Electron neutrino

Meson resonances

Muon neutrino

CP violation in K meson decay

Scaling in deep inelastic electron scattering

Solar neutrino deficit

Neutral weak currents

J/ψ

Charmed mesons, baryons

τ lepton

Bottom mesons

Gluons

1940

1950

1960

1970

1980

Quantum electrodynamics

Cabibbo angle

Yang-Mills gauge theory

The Eightfold Way

Higgs mechanism

Quark substructure

Color quantum number

Weak/electromagnetic unification

Partons

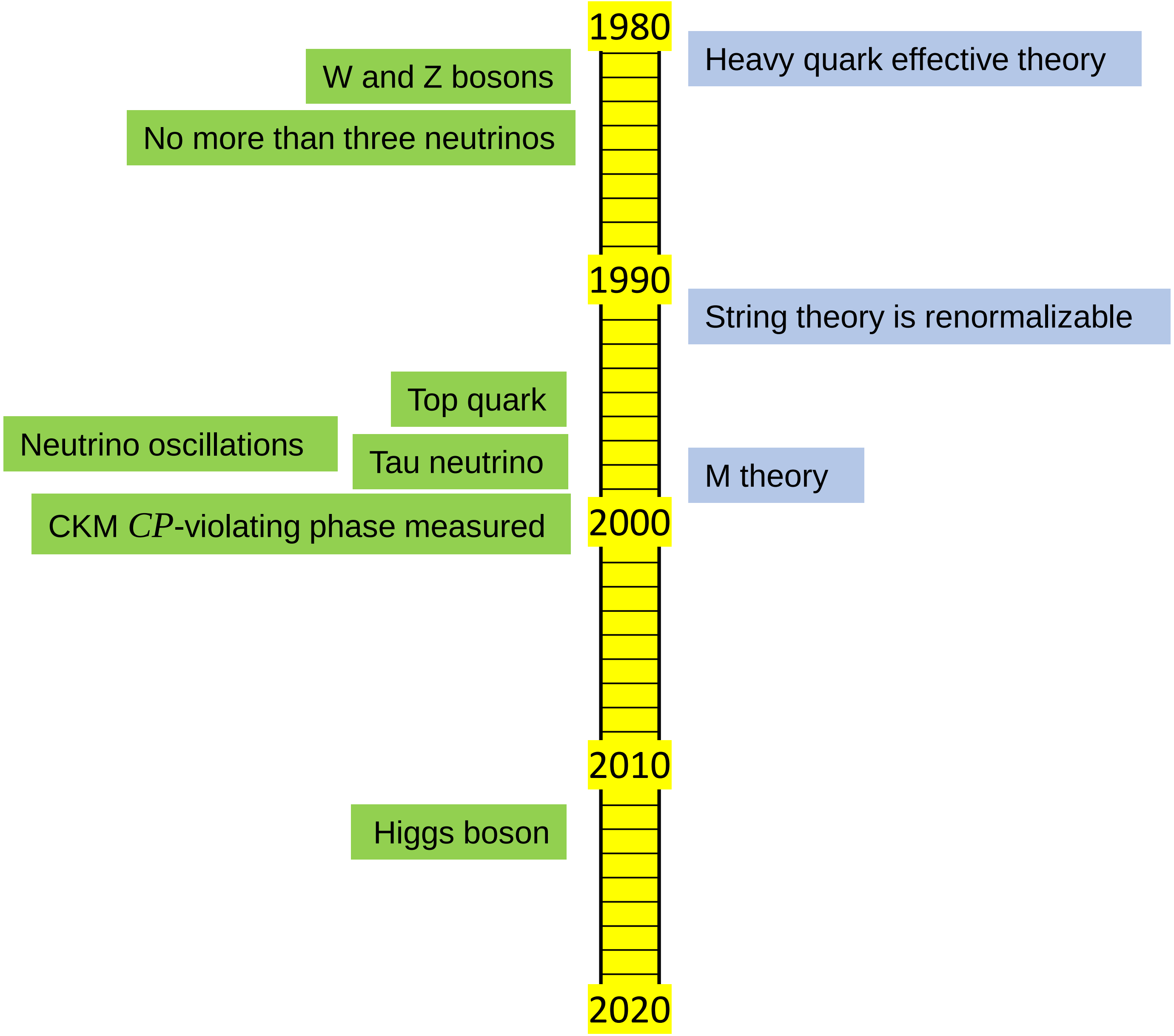
The GIM mechanism

String theory

Asymptotic freedom

Kobayashi-Maskawa quark matrix

PMNS neutrino matrix



1980

W and Z bosons

Heavy quark effective theory

No more than three neutrinos

1990

String theory is renormalizable

Top quark

Neutrino oscillations

Tau neutrino

M theory

CKM *CP*-violating phase measured

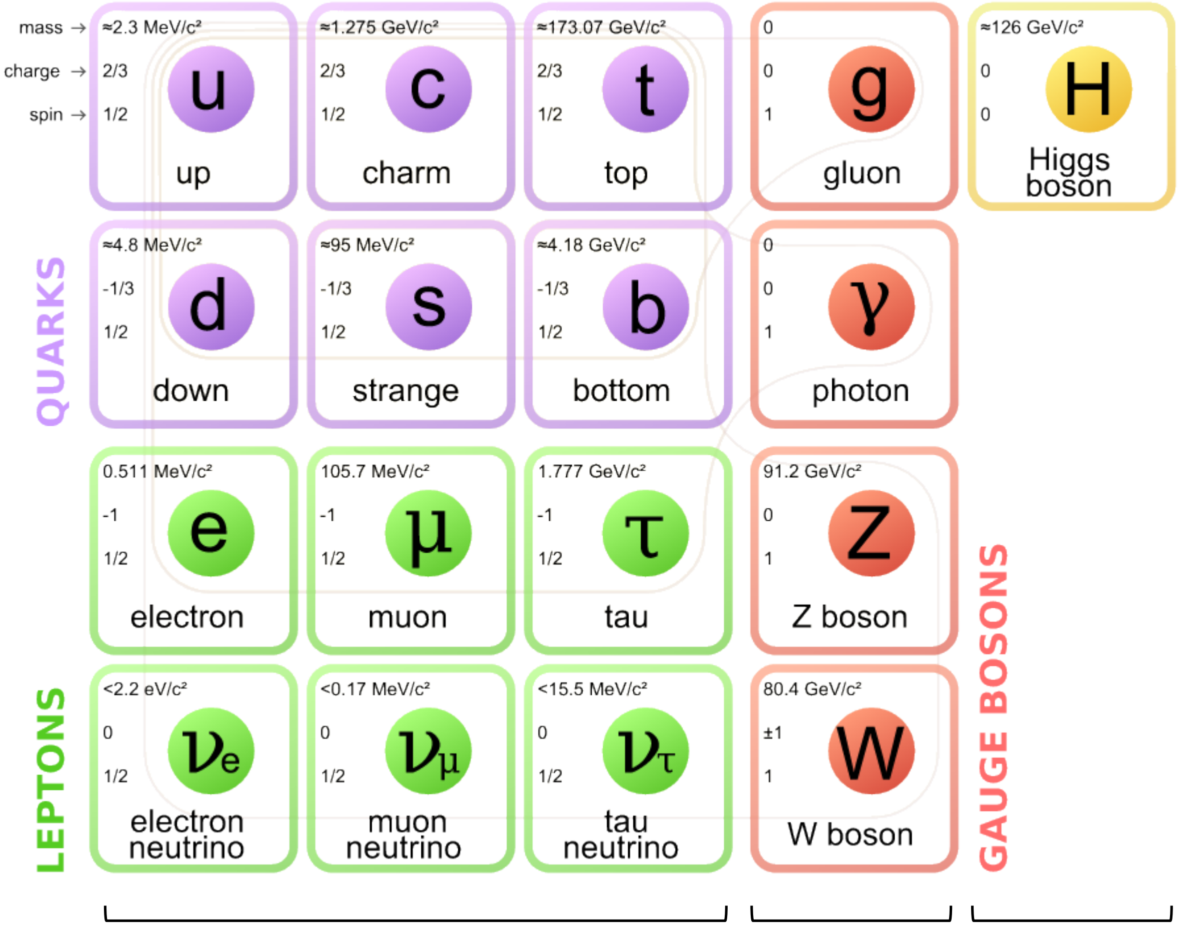
2000

2010

Higgs boson

2020

The Standard Model

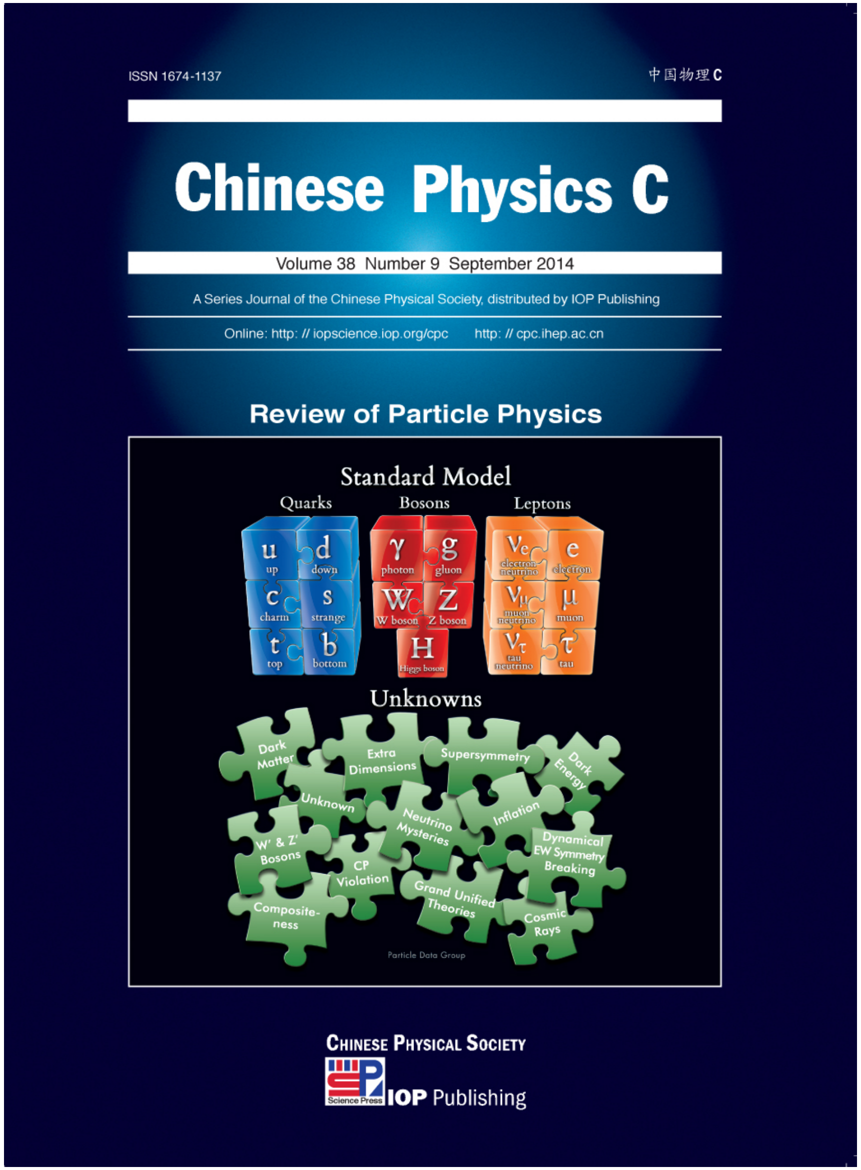


mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	
	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson	GAUGE BOSONS
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson	

fermions
s=1/2

bosons
s=1

scalar
s=0



ISSN 1674-1137

中国物理 C

Chinese Physics C

Volume 38 Number 9 September 2014

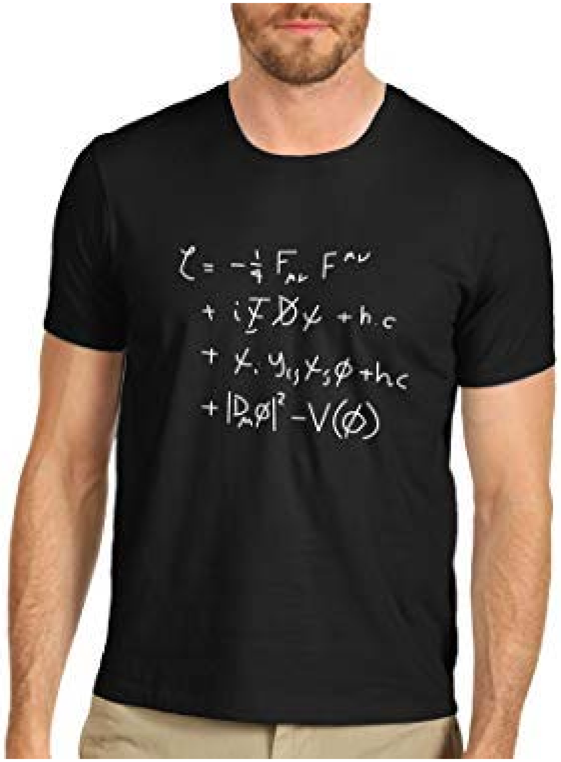
A Series Journal of the Chinese Physical Society, distributed by IOP Publishing

Online: http: // iopscience.iop.org/cpc http: // cpc.ihep.ac.cn

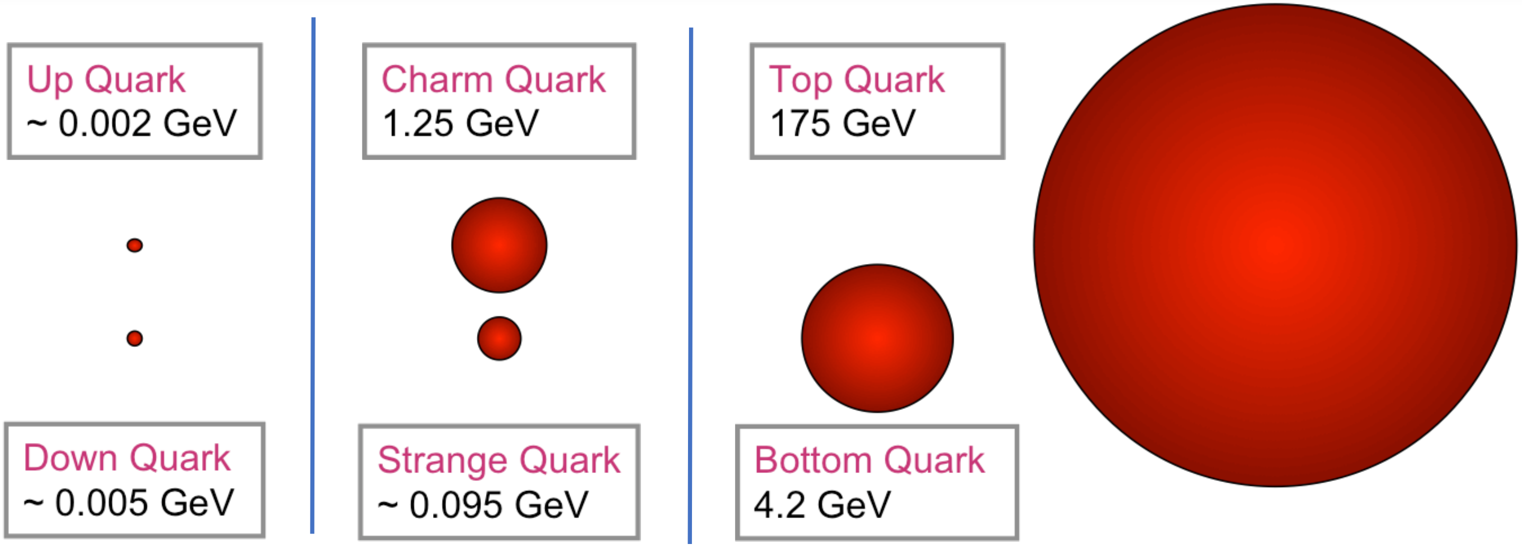
Review of Particle Physics

CHINESE PHYSICAL SOCIETY

Science Press IOP Publishing


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c$
$+ \psi_i y_{ij} \psi_j \phi + h.c$
$+ |D_\mu \phi|^2 - V(\phi)$

Three families of quarks and leptons



Up Quark
~ 0.002 GeV

Down Quark
~ 0.005 GeV

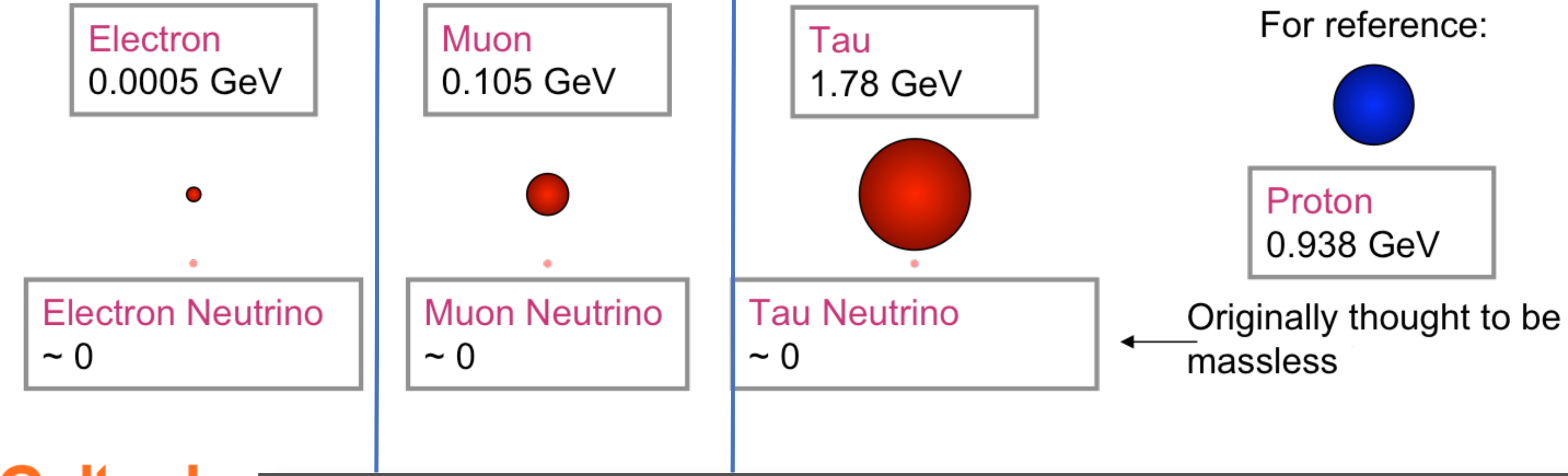
Charm Quark
1.25 GeV

Strange Quark
~ 0.095 GeV

Top Quark
175 GeV

Bottom Quark
4.2 GeV

The pattern of relative masses remains a mystery as does the reason for there being three generations of quarks and leptons



Electron
0.0005 GeV

Electron Neutrino
~ 0

Muon
0.105 GeV

Muon Neutrino
~ 0

Tau
1.78 GeV

Tau Neutrino
~ 0

← Originally thought to be massless

For reference:

Proton
0.938 GeV

The neutron

- In 1932 Chadwick proved the existence of a neutral particle with approximately the same mass as the proton
- He scattered α particles from a beryllium target
- Particles ejected from target were not deflected by an electric field, hence they were electrically **neutral**
- He determined the particle mass by measuring deflection in scattering from from gasses with differing atomic number – it was **similar to a proton**
- This discovery led to the concept of **isotopic spin**: two particles which are actually different “spin” projections of the same object

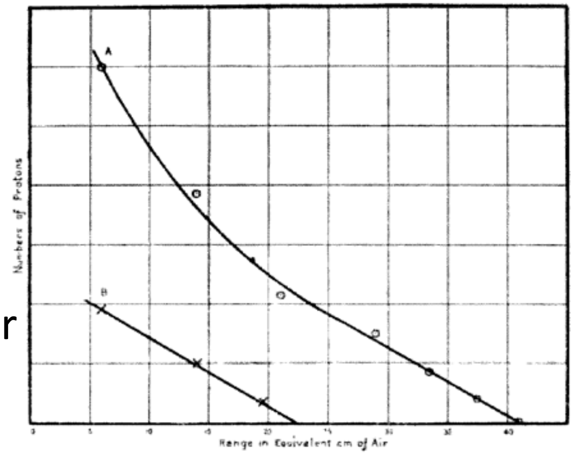
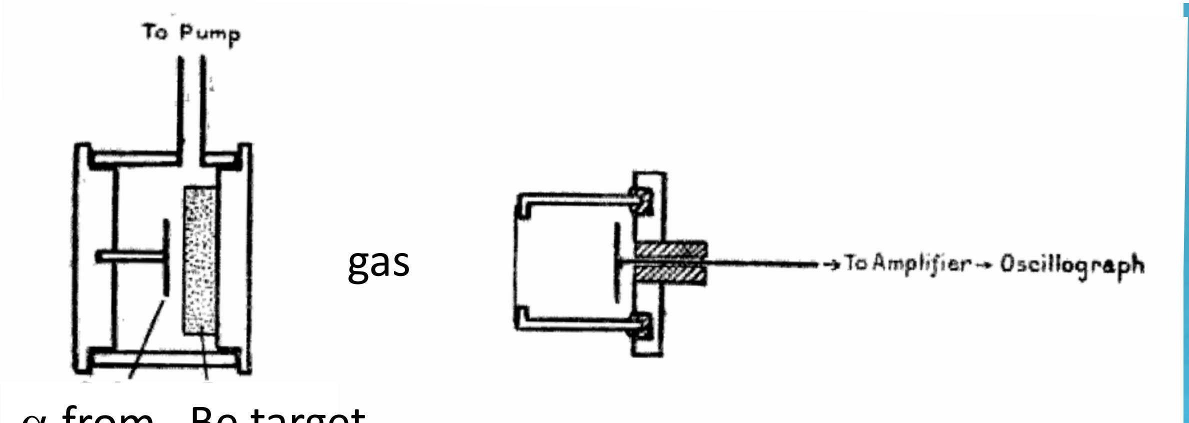


FIG. 2.



gas

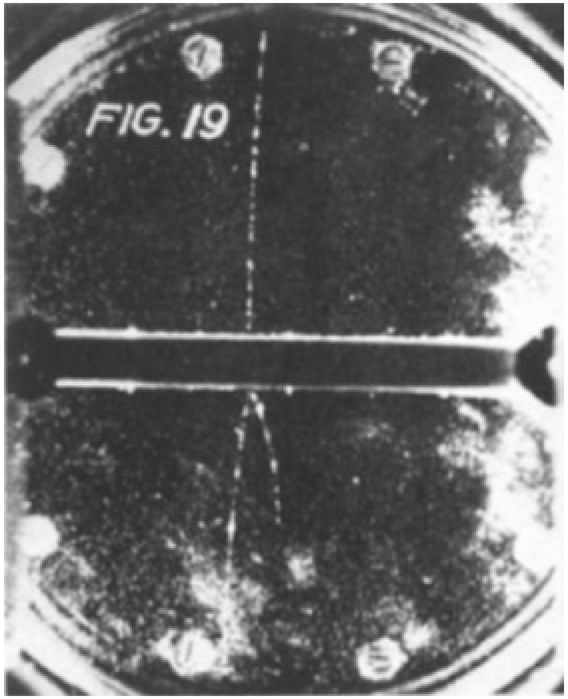
α from Po source

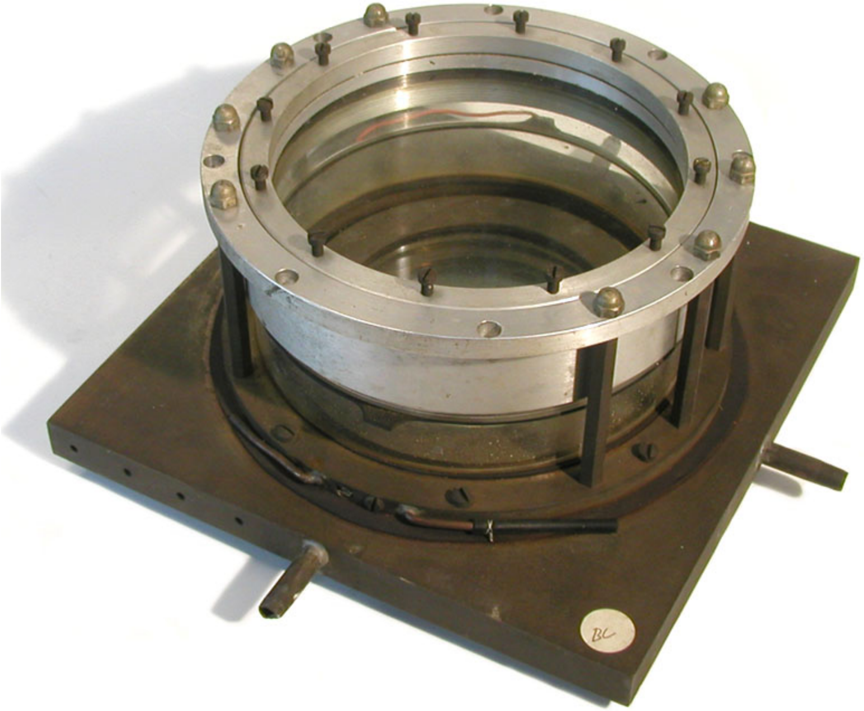
Be target

FIG. 1.

The muon

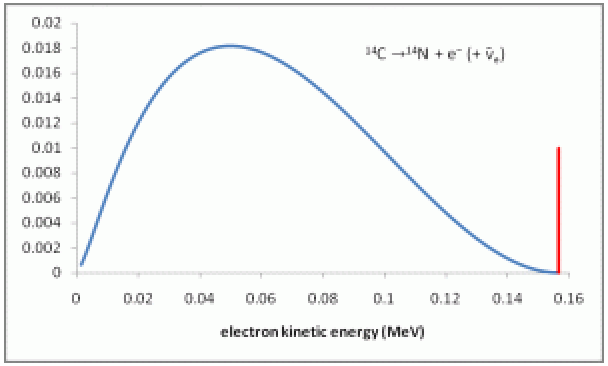
- In 1935 Anderson and Neddemeyer found a highly penetrating charged particle
- This was regarded first as a heavy electron, and then speculatively identified with the mesotron, the heavy quantum postulated by Yukawa as the carrier of the short-range strong nuclear force



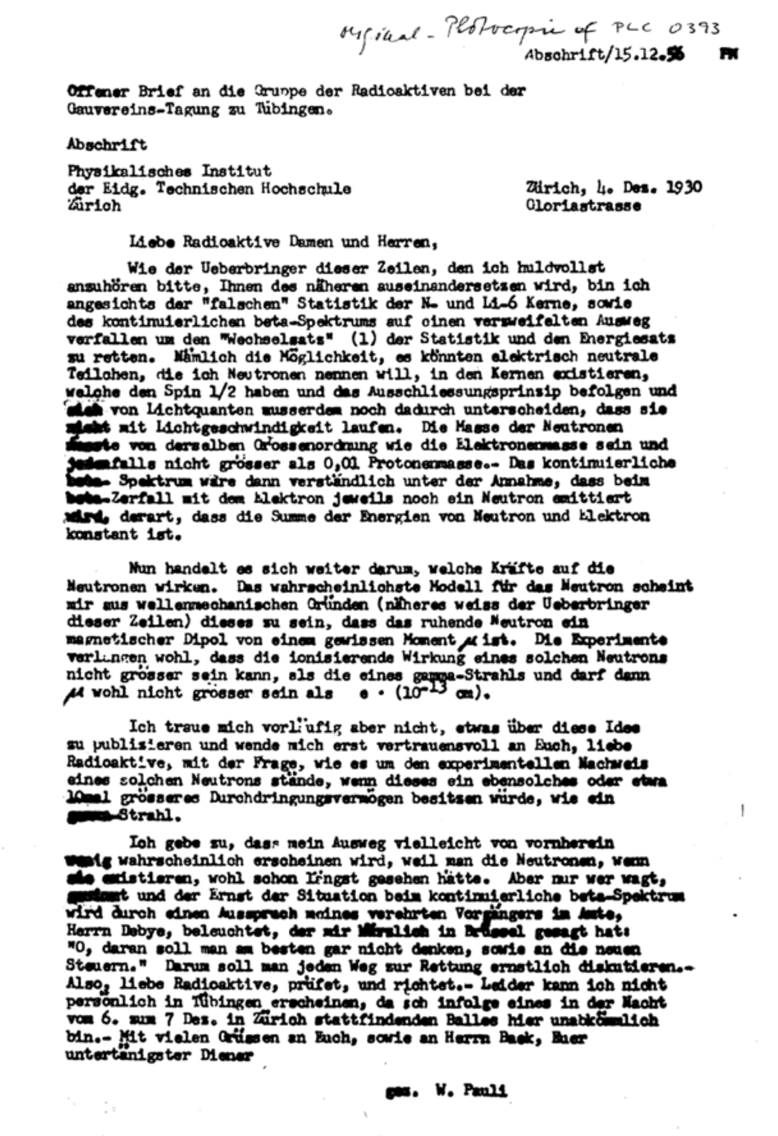


The neutrino

- Wolfgang Pauli in 1930 postulated the existence of a neutral spin ½ particle, which he called the "neutron", later the "neutrino", as a "desperate remedy" in order to preserve the concepts of conservation of energy and angular momentum



- Neutrinos were not actually detected until 1956 by Reines and Cowan



Original - Photocopie of PLC 0393

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

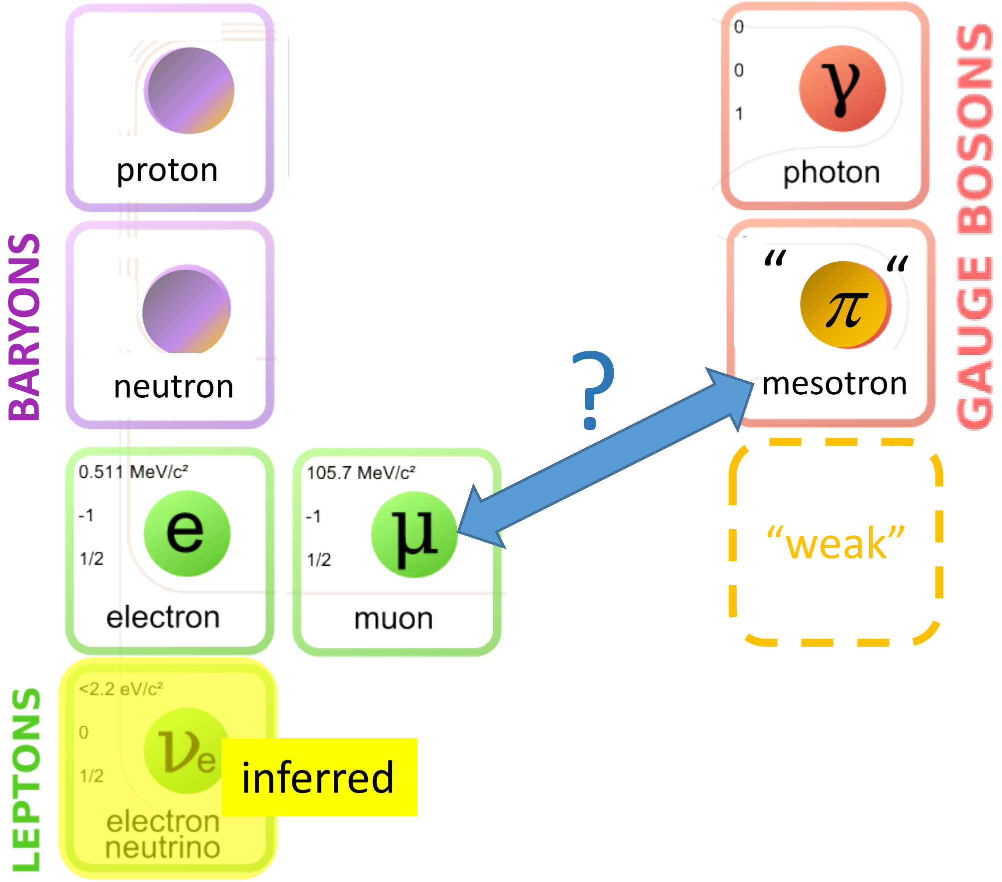
Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}\ \mathrm{cm})$.

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

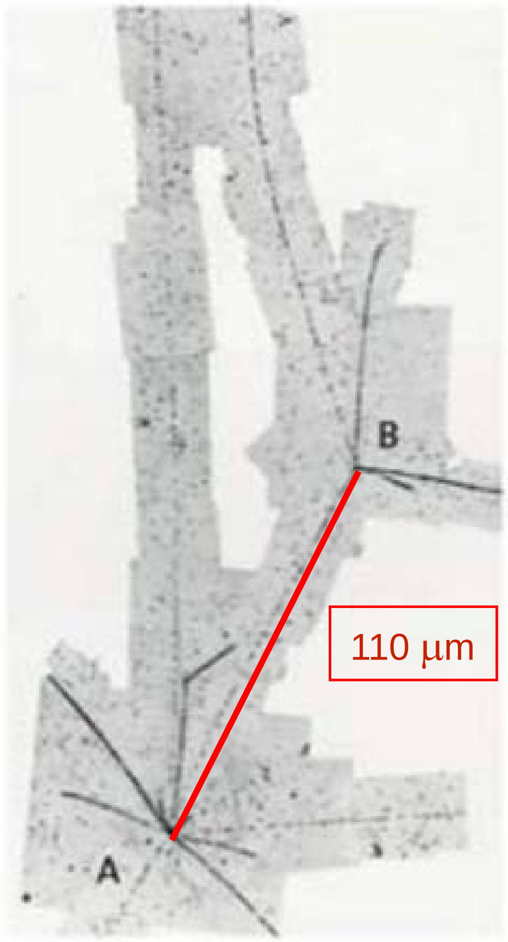
gez. W. Pauli

The Standard Model circa 1937



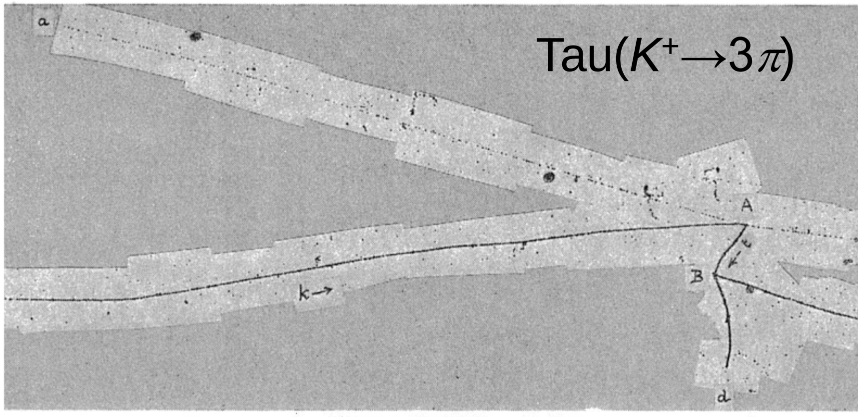
The pion

- In 1935 Yukawa introduced the concept of the (short range) force between nucleons being transmitted by a massive particle – the mesotron
    - From the range of the nuclear force, this particle should have a mass about 1/7 that of the proton
- It was first thought that Anderson's mesotron (muon) was Yukawa's strong force carrier
    - However, Pontecorvo pointed out that while the mass was in the correct range, the particle's observed ability to penetrate matter precluded the required strong interaction coupling strength
- The correct particle, the π meson, or pion, was finally found in 1947 by Lattes, Occhialini and Powell in nuclear emulsions
- In modern language, the pion is in fact not the transmitter of the force (*cf.* gluons), but is a mesonic state composed of a quark and an antiquark



New particles began to proliferate

- Using cosmic rays and new accelerators, with emulsions, cloud chambers and bubble chambers, a variety of new particles were soon identified
- Many of these demonstrated branching, the V particles



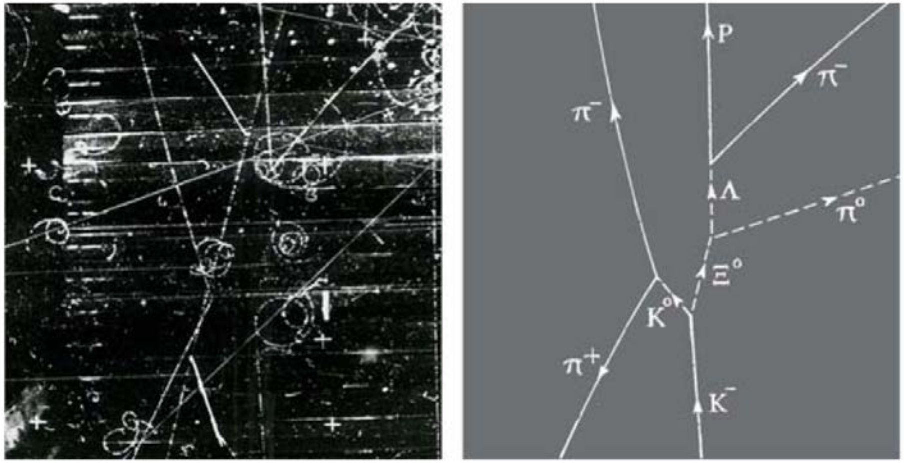
Tau($K^+ \rightarrow 3\pi$)

Observer : Mrs. W. J. van der Merwe

By Miss R. BROWN, U. CAMERINI, P. H. FOWLER, H. MUIRHEAD
and Prof. C. F. POWELL
H. H. Wills Physical Laboratory, University of Bristol

and D. M. RITSON
Clarendon Laboratory, Oxford

emulsions

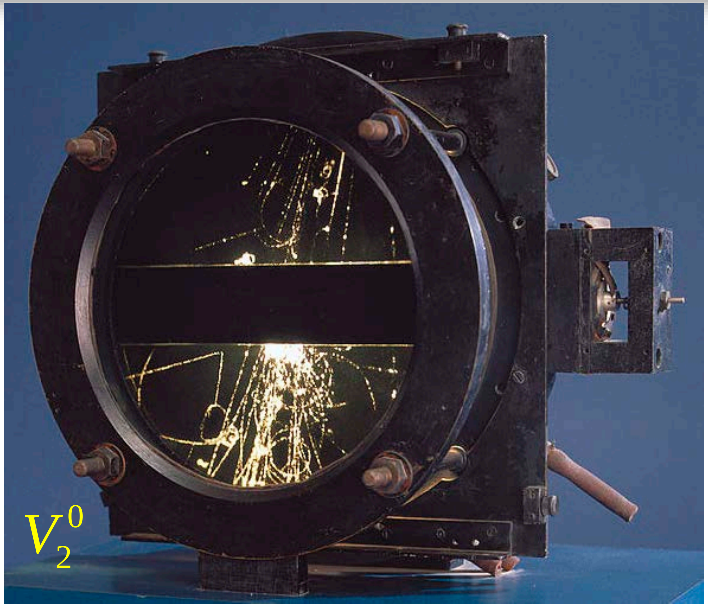


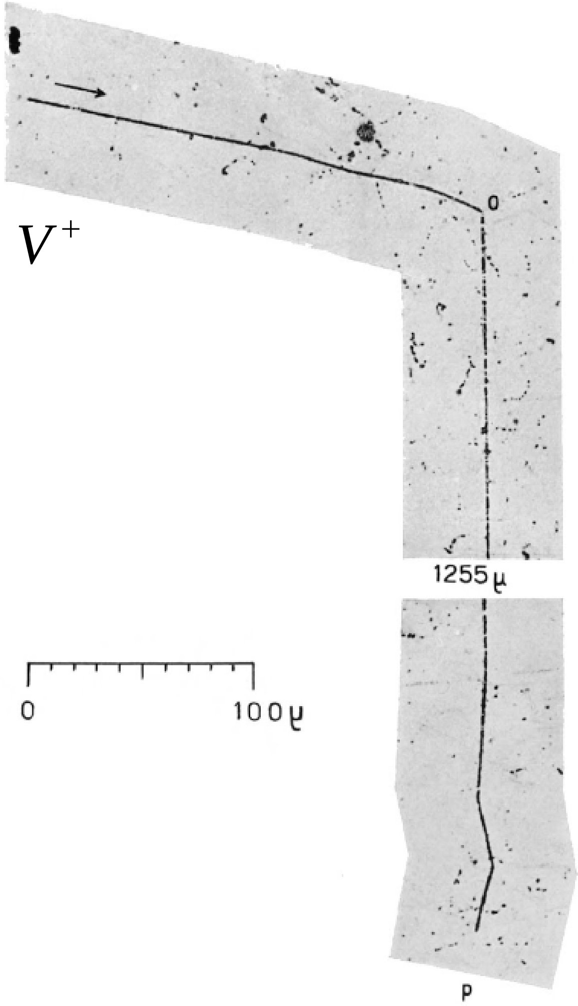
$K^- p \rightarrow K^0 \Xi^0$

$\Xi^0 \rightarrow \Lambda^0 \pi^0$

LBL 15” hydrogen bubble chamber

The *V* particles





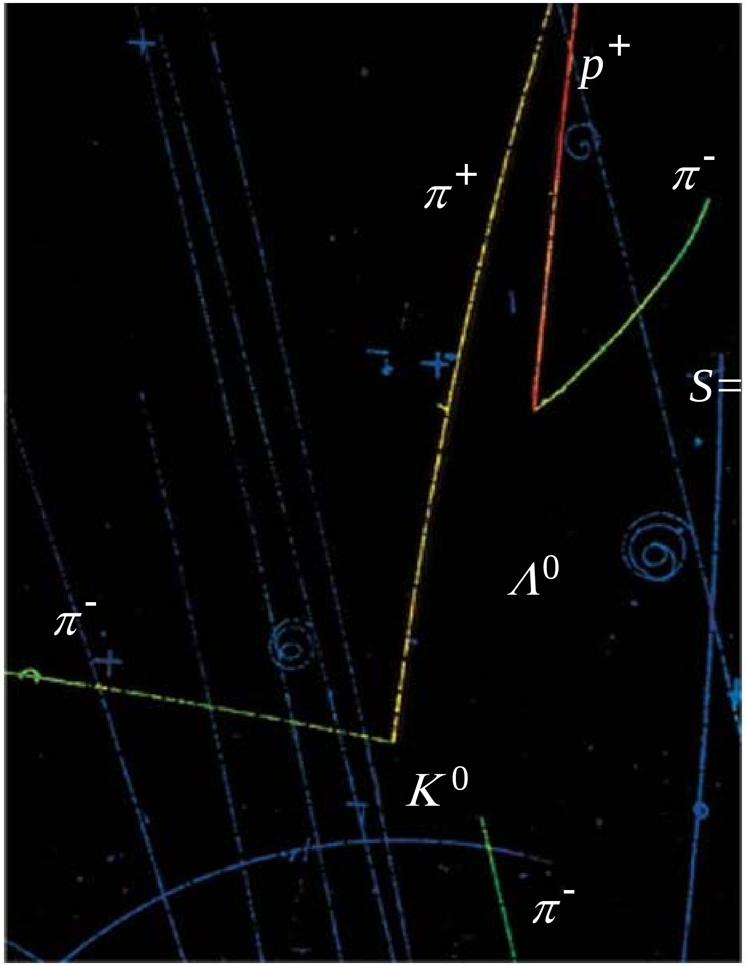
Original name	Current name	
τ	$K^+ \to \pi^+\pi^+\pi^-$	$(K_{\pi 3})$
V_1^0	$\Lambda^0 \to p\pi^-$	
$V_2^0(\theta^0)$	$K_S^0 \to \pi^+\pi^-$	
κ	$K^+ \to \mu^+\nu_\mu$	$(K_{\mu 2})$
	$K^+ \to \mu^+\pi^0\nu_\mu$	$(K_{\mu 3})$
$\chi(\theta^+)$	$K^+ \to \pi^+\pi^0$	$(K_{\pi 2})$
V^+, Λ^+	$\Sigma^+ \to p\pi^0, n\pi^+$	

Associated production

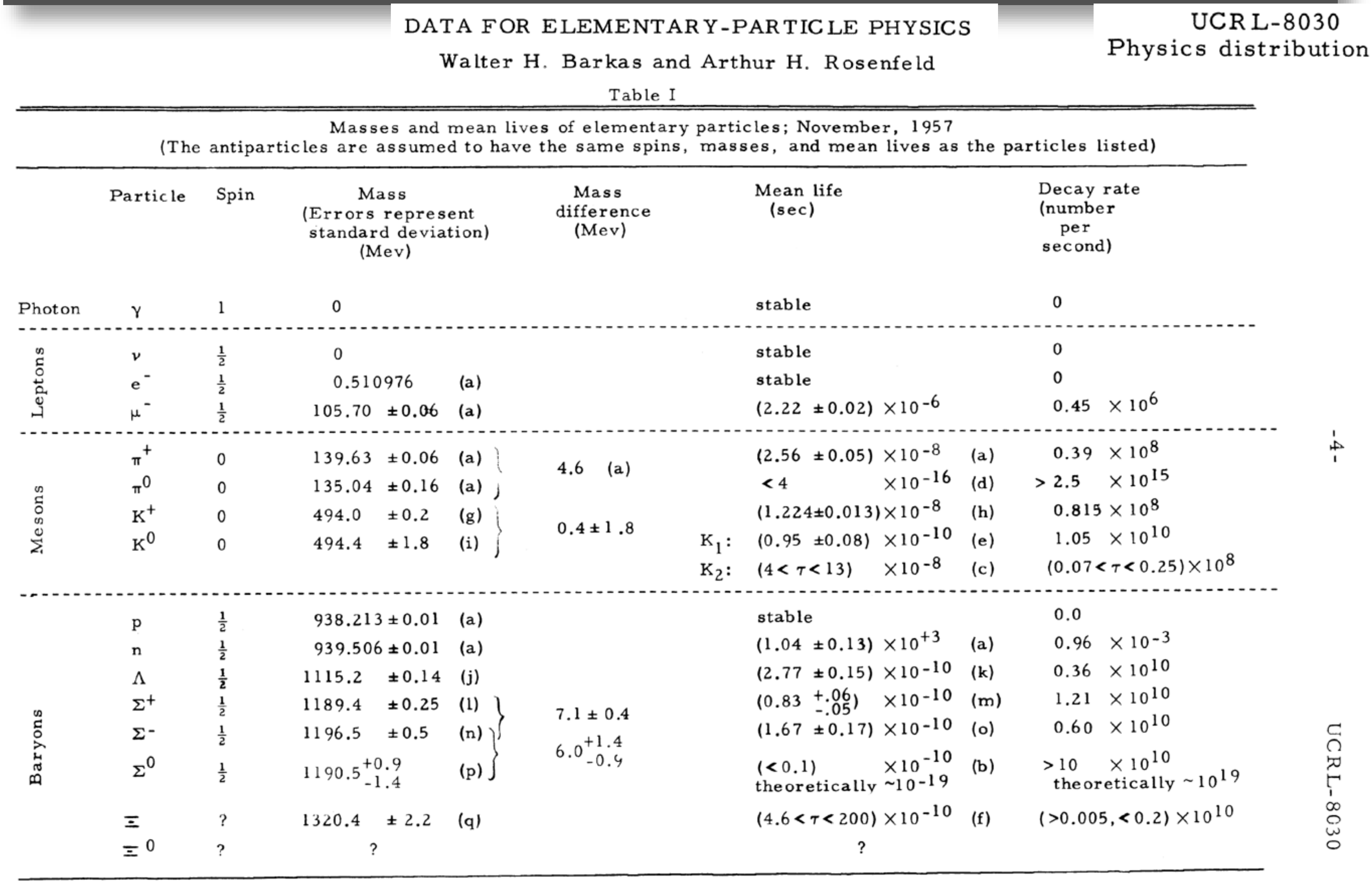
- The V particles motivated assignment of a **new quantum number** S for “strangeness” (Gell-Mann, Pais)
- S is **conserved** in the strong interaction process of strange particle production (“associated production”), but **violated** in the weak decay of the strange baryon and meson

$$\begin{array}{lcccc} S & 0 & 0 & -1 & +1 \\ & \pi^- & p \to & \Lambda^0 & K^0 \\ & & & \searrow & \searrow \\ & & & p\,\pi^- & \pi^+\pi^- \\ S & & & 0\ \ 0 & 0\ \ 0 \end{array}$$

- The identification of the S quantum number with the s (strange) quark was still a decade away



The first Review of Particle Properties - 1958



DATA FOR ELEMENTARY-PARTICLE PHYSICS

Walter H. Barkas and Arthur H. Rosenfeld

UCRL-8030
Physics distribution

Table I

Masses and mean lives of elementary particles; November, 1957
(The antiparticles are assumed to have the same spins, masses, and mean lives as the particles listed)

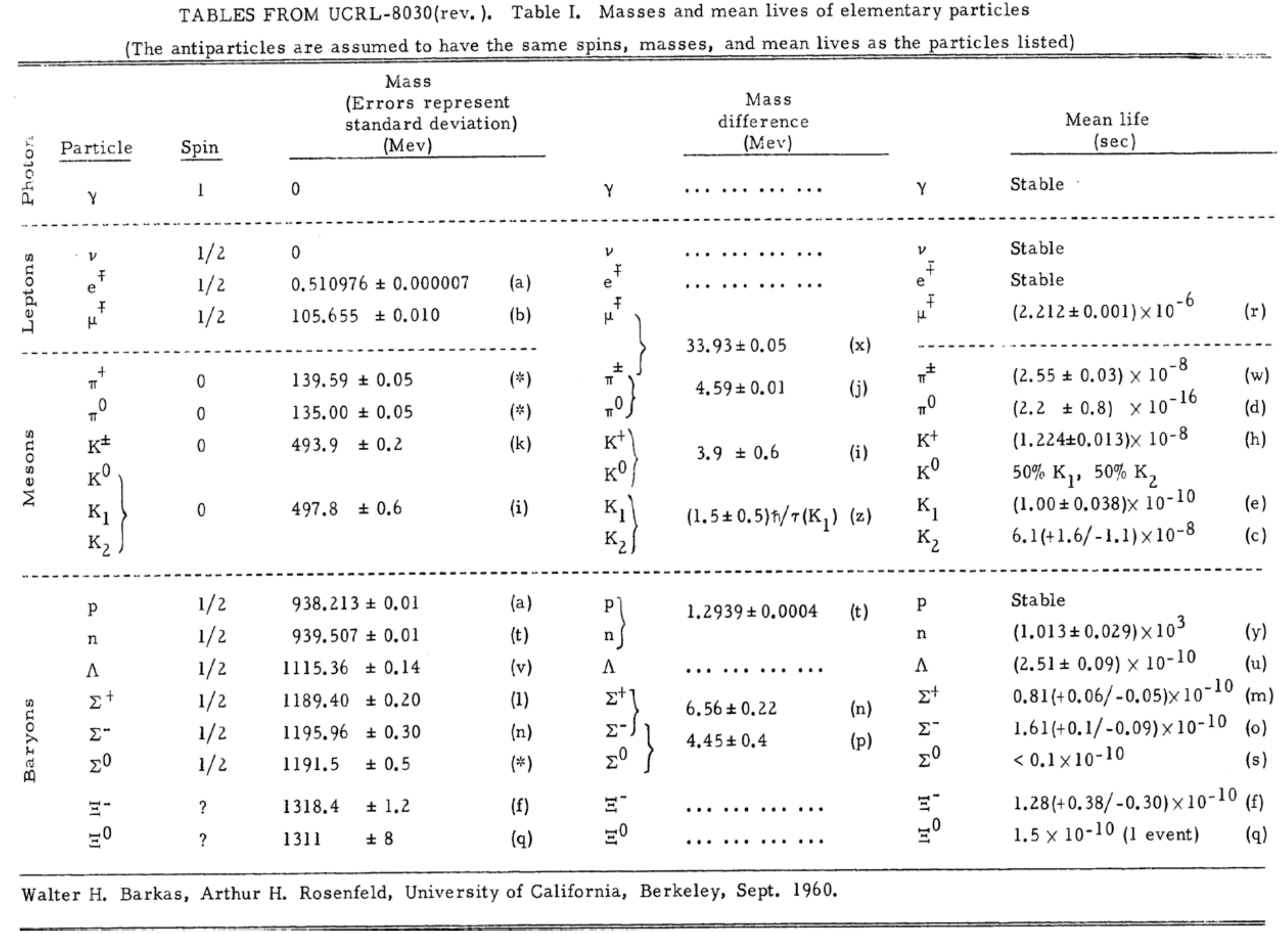
	Particle	Spin	Mass (Errors represent standard deviation) (Mev)		Mass difference (Mev)	Mean life (sec)		Decay rate (number per second)
Photon	γ	1	0			stable		0
Leptons	ν	$\frac{1}{2}$	0			stable		0
	e^-	$\frac{1}{2}$	0.510976	(a)		stable		0
	μ^-	$\frac{1}{2}$	105.70 ± 0.06	(a)		$(2.22 \pm 0.02) \times 10^{-6}$		0.45×10^{6}
Mesons	π^+	0	139.63 ± 0.06	(a)	4.6 (a)	$(2.56 \pm 0.05) \times 10^{-8}$	(a)	0.39×10^{8}
	π^0	0	135.04 ± 0.16	(a)		$< 4 \times 10^{-16}$	(d)	$> 2.5 \times 10^{15}$
	K^+	0	494.0 ± 0.2	(g)	0.4 ± 1.8	$(1.224 \pm 0.013) \times 10^{-8}$	(h)	0.815×10^{8}
	K^0	0	494.4 ± 1.8	(i)		K_1: $(0.95 \pm 0.08) \times 10^{-10}$	(e)	1.05×10^{10}
						K_2: $(4 < \tau < 13) \times 10^{-8}$	(c)	$(0.07 < \tau < 0.25) \times 10^{8}$
Baryons	p	$\frac{1}{2}$	938.213 ± 0.01	(a)		stable		0.0
	n	$\frac{1}{2}$	939.506 ± 0.01	(a)		$(1.04 \pm 0.13) \times 10^{+3}$	(a)	0.96×10^{-3}
	Λ	$\frac{1}{2}$	1115.2 ± 0.14	(j)		$(2.77 \pm 0.15) \times 10^{-10}$	(k)	0.36×10^{10}
	Σ^+	$\frac{1}{2}$	1189.4 ± 0.25	(l)	7.1 ± 0.4	$(0.83 {}^{+.06}_{-.05}) \times 10^{-10}$	(m)	1.21×10^{10}
	Σ^-	$\frac{1}{2}$	1196.5 ± 0.5	(n)	$6.0^{+1.4}_{-0.9}$	$(1.67 \pm 0.17) \times 10^{-10}$	(o)	0.60×10^{10}
	Σ^0	$\frac{1}{2}$	$1190.5^{+0.9}_{-1.4}$	(p)		$(< 0.1) \times 10^{-10}$ theoretically $\sim 10^{-19}$	(b)	$> 10 \times 10^{10}$ theoretically $\sim 10^{19}$
	Ξ	?	1320.4 ± 2.2	(q)		$(4.6 < \tau < 200) \times 10^{-10}$	(f)	$(> 0.005, < 0.2) \times 10^{10}$
	Ξ^0	?	?			?		

-4-

UCRL-8030

20 pages, including tables of material properties, cross sections, etc.. The particle list was a single page.

The 1961 update



TABLES FROM UCRL-8030(rev.). Table I. Masses and mean lives of elementary particles

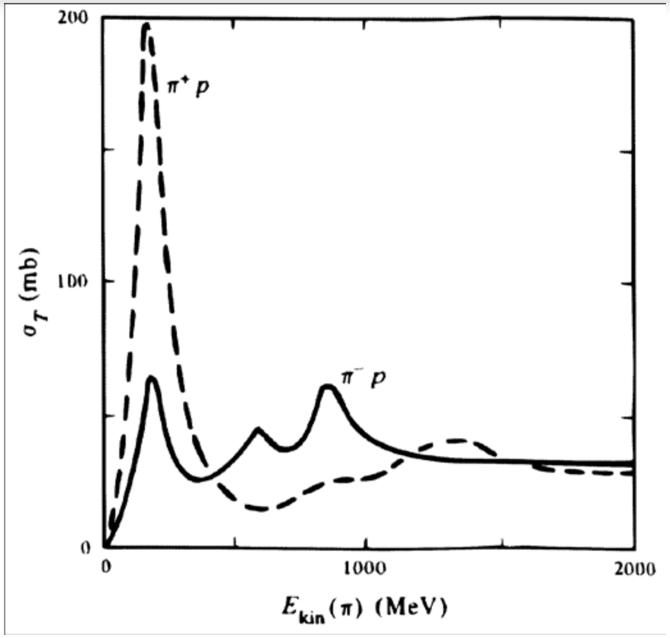
(The antiparticles are assumed to have the same spins, masses, and mean lives as the particles listed)

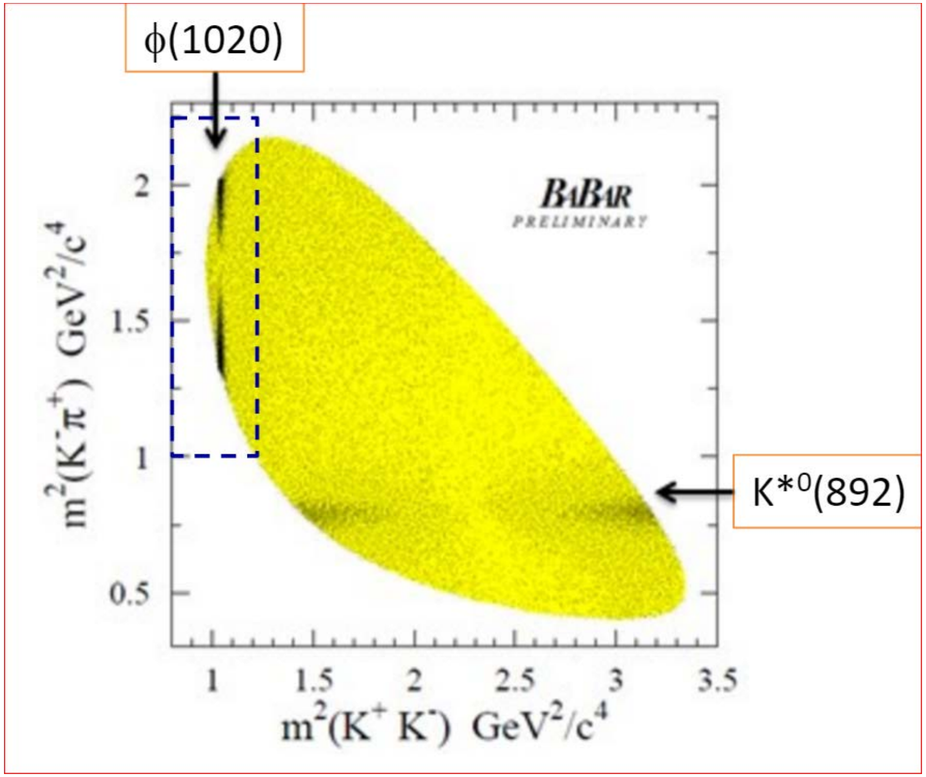
	Particle	Spin	Mass (Errors represent standard deviation) (Mev)			Mass difference (Mev)			Mean life (sec)	
Photon	γ	1	0		γ	... ...		γ	Stable	
Leptons	ν	1/2	0		ν	... ...		ν	Stable	
	$e^{\mp}$	1/2	0.510976 ± 0.000007	(a)	$e^{\mp}$	... ...		$e^{\mp}$	Stable	
	$\mu^{\mp}$	1/2	105.655 ± 0.010	(b)	$\mu^{\mp}$	33.93 ± 0.05	(x)	$\mu^{\mp}$	$(2.212 \pm 0.001) \times 10^{-6}$	(r)
Mesons	π^{+}	0	139.59 ± 0.05	(*)	$\pi^{\pm}$	4.59 ± 0.01	(j)	$\pi^{\pm}$	$(2.55 \pm 0.03) \times 10^{-8}$	(w)
	π^{0}	0	135.00 ± 0.05	(*)	π^{0}			π^{0}	$(2.2 \pm 0.8) \times 10^{-16}$	(d)
	$K^{\pm}$	0	493.9 ± 0.2	(k)	K^{+}	3.9 ± 0.6	(i)	K^{+}	$(1.224 \pm 0.013) \times 10^{-8}$	(h)
	K^{0}	0	497.8 ± 0.6	(i)	K^{0}			K^{0}	50% K_1, 50% K_2	
	K_1				K_1	$(1.5 \pm 0.5)\hbar/\tau(K_1)$	(z)	K_1	$(1.00 \pm 0.038) \times 10^{-10}$	(e)
	K_2				K_2			K_2	$6.1(+1.6/-1.1) \times 10^{-8}$	(c)
Baryons	p	1/2	938.213 ± 0.01	(a)	p	1.2939 ± 0.0004	(t)	p	Stable	
	n	1/2	939.507 ± 0.01	(t)	n			n	$(1.013 \pm 0.029) \times 10^{3}$	(y)
	Λ	1/2	1115.36 ± 0.14	(v)	Λ	... ...		Λ	$(2.51 \pm 0.09) \times 10^{-10}$	(u)
	Σ^{+}	1/2	1189.40 ± 0.20	(l)	Σ^{+}	6.56 ± 0.22	(n)	Σ^{+}	$0.81(+0.06/-0.05) \times 10^{-10}$	(m)
	Σ^{-}	1/2	1195.96 ± 0.30	(n)	Σ^{-}	4.45 ± 0.4	(p)	Σ^{-}	$1.61(+0.1/-0.09) \times 10^{-10}$	(o)
	Σ^{0}	1/2	1191.5 ± 0.5	(*)	Σ^{0}			Σ^{0}	$< 0.1 \times 10^{-10}$	(s)
	Ξ^{-}	?	1318.4 ± 1.2	(f)	Ξ^{-}	... ...		Ξ^{-}	$1.28(+0.38/-0.30) \times 10^{-10}$	(f)
	Ξ^{0}	?	1311 ± 8	(q)	Ξ^{0}	... ...		Ξ^{0}	1.5×10^{-10} (1 event)	(q)

Walter H. Barkas, Arthur H. Rosenfeld, University of California, Berkeley, Sept. 1960.

Resonances

- The first baryon resonance, the $\Delta(1235)$, was found by Fermi in πp scattering
- Many others soon followed





- The advent of the **Dalitz plot** provided another fruitful avenue to explore resonances
- Example: $D^+ \rightarrow K^+K^-\pi^+$
- The Dalitz plot construction allowed isolation of resonant states and determination of their spin and parity

One page of possible resonances

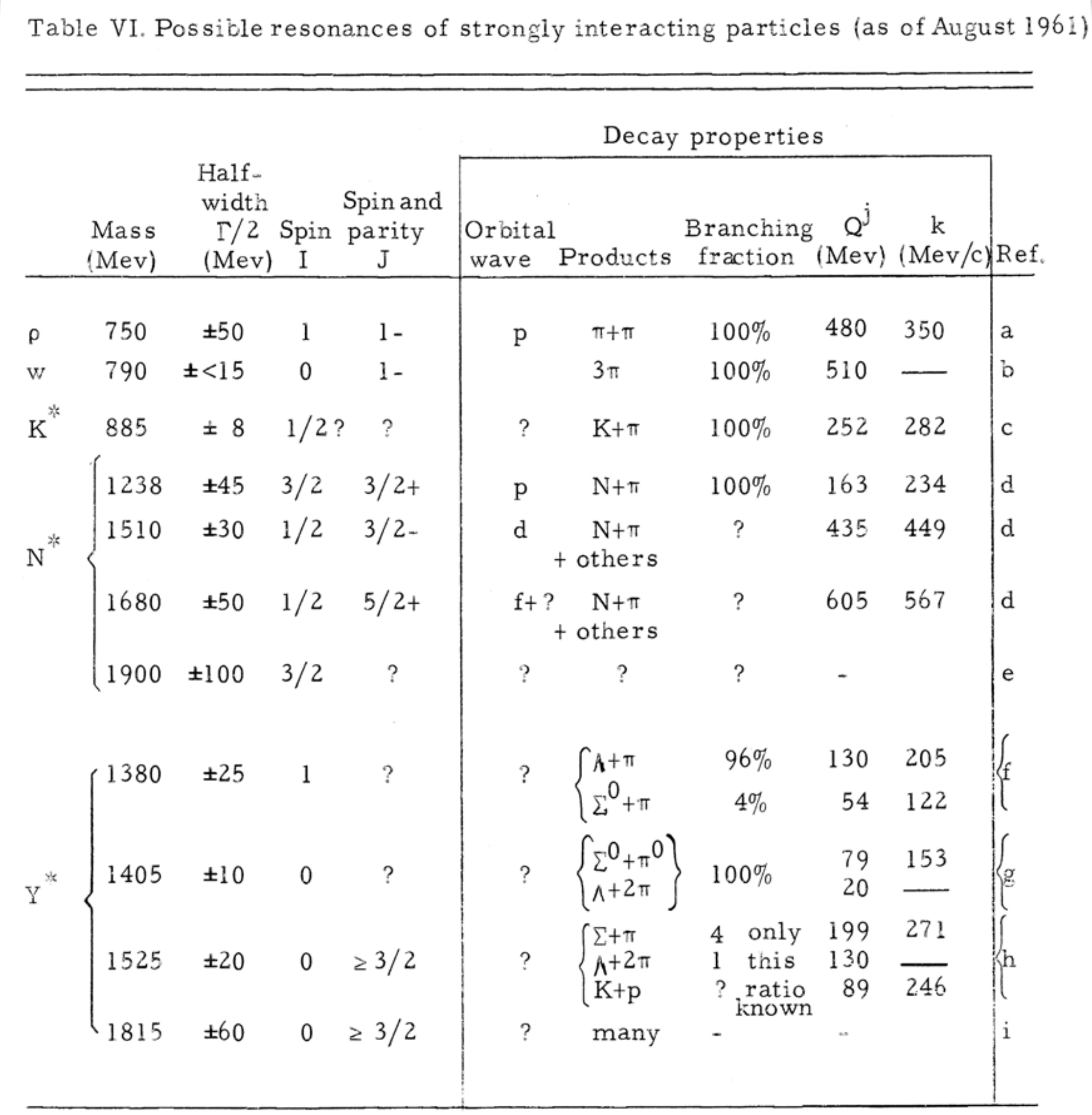
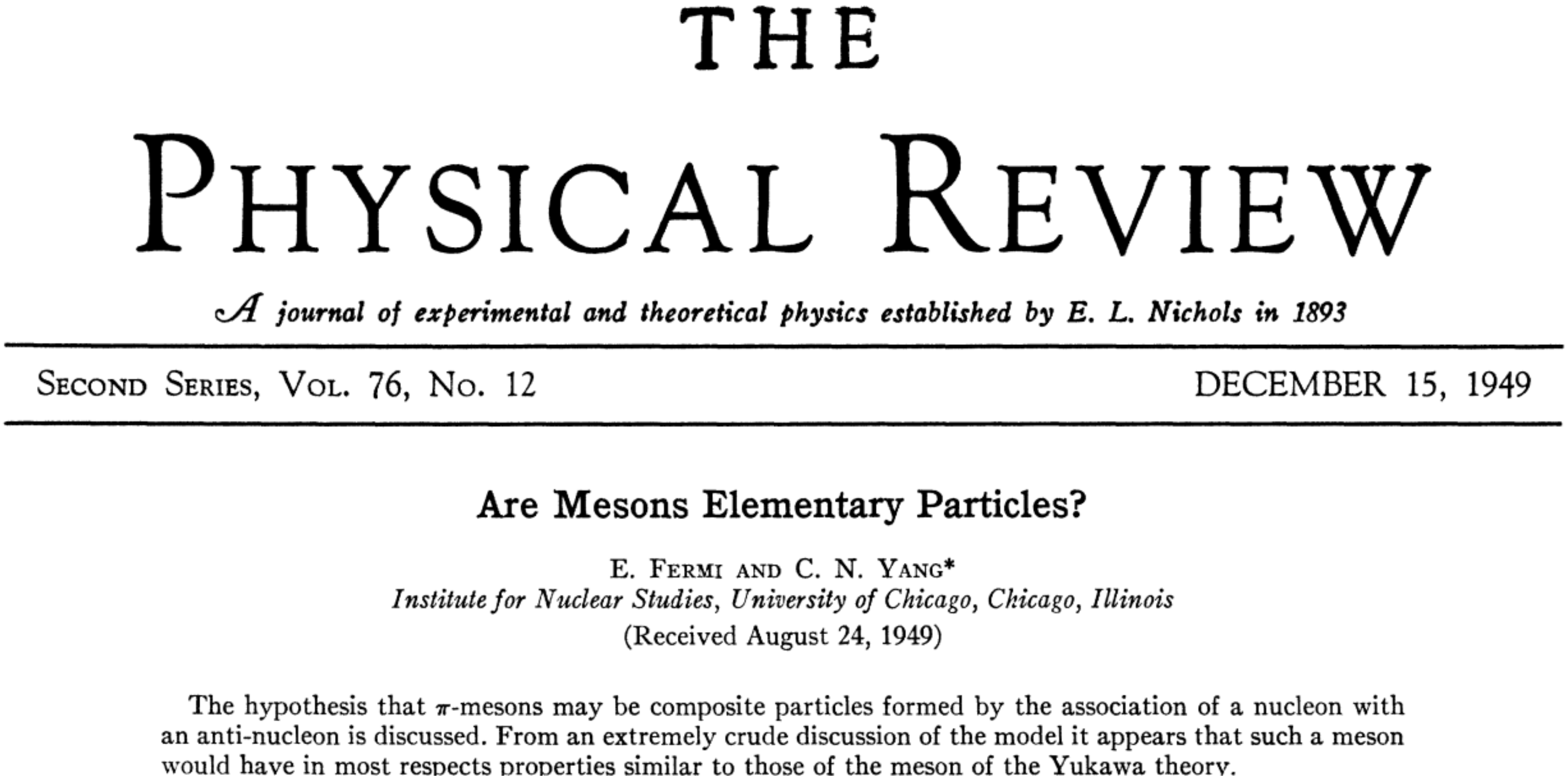


Table VI. Possible resonances of strongly interacting particles (as of August 1961)

	Mass (Mev)	Half-width $\Gamma/2$ (Mev)	Spin I	Spin and parity J	Decay properties					Ref.
					Orbital wave	Products	Branching fraction	Q^j (Mev)	k (Mev/c)	
ρ	750	±50	1	1-	p	$\pi+\pi$	100%	480	350	a
ω	790	±<15	0	1-		3π	100%	510	—	b
K^*	885	± 8	1/2 ?	?	?	$K+\pi$	100%	252	282	c
N^*	1238	±45	3/2	3/2+	p	$N+\pi$	100%	163	234	d
	1510	±30	1/2	3/2-	d	$N+\pi$ + others	?	435	449	d
	1680	±50	1/2	5/2+	f+ ?	$N+\pi$ + others	?	605	567	d
	1900	±100	3/2	?	?	?	?	-		e
Y^*	1380	±25	1	?	?	$\Lambda+\pi$ $\Sigma^0+\pi$	96% 4%	130 54	205 122	f
	1405	±10	0	?	?	$\Sigma^0+\pi^0$ $\Lambda+2\pi$	100%	79 20	153 —	g
	1525	±20	0	≥ 3/2	?	$\Sigma+\pi$ $\Lambda+2\pi$ $K+p$	4 1 ? only this ratio known	199 130 89	271 — 246	h
	1815	±60	0	≥ 3/2	?	many	-	-		i

What is an elementary particle?

As the number of particles proliferated, Pauli famously remarked
“Had I foreseen that, I would have gone into botany.”
More seriously, the question of what is truly elementary came to the fore



THE

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 76, NO. 12 DECEMBER 15, 1949

Are Mesons Elementary Particles?

E. FERMI AND C. N. YANG*
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received August 24, 1949)

The hypothesis that π-mesons may be composite particles formed by the association of a nucleon with an anti-nucleon is discussed. From an extremely crude discussion of the model it appears that such a meson would have in most respects properties similar to those of the meson of the Yukawa theory.

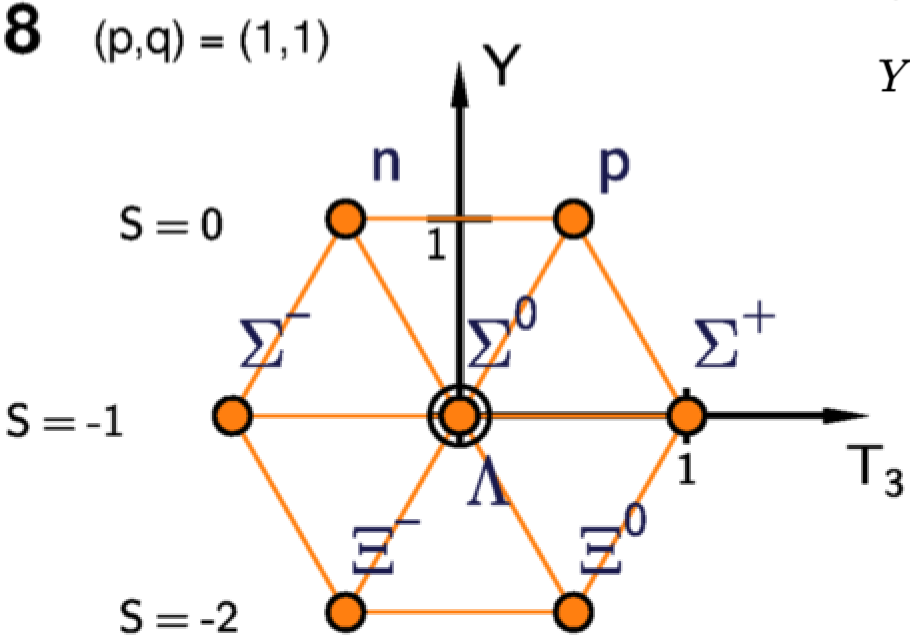
The answer would not be found for nearly fifteen years

The Eightfold Way

- Attempts to organize the growing number of hadron states culminated in the idea of generalizing isotopic spin, incorporating strangeness, and identifying particle states with the representations of the Lie group SU(3). Gell-Mann called this the Eightfold Way. Ne'eman had a similar, but less poetically named, scheme
  - In the limit of SU(3) symmetry, a given representation would have a single mass
  - The pattern of states in a given multiplet due to symmetry breaking could be calculated: the Gell-Mann-Nishijima formula

$$Q = I_3 + \frac{1}{2}Y$$

$$Y = 2(Q - I_3)$$



- The masses obey the Gell-Mann – Okubo formula

$$M = a_0 + a_1 S + a_2\left[I\left(I+1\right) - \frac{1}{4}S^2\right]$$

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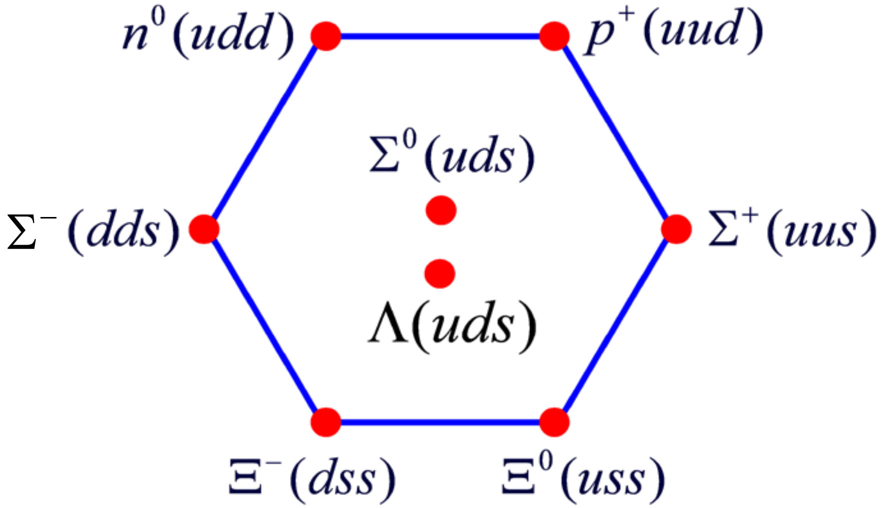

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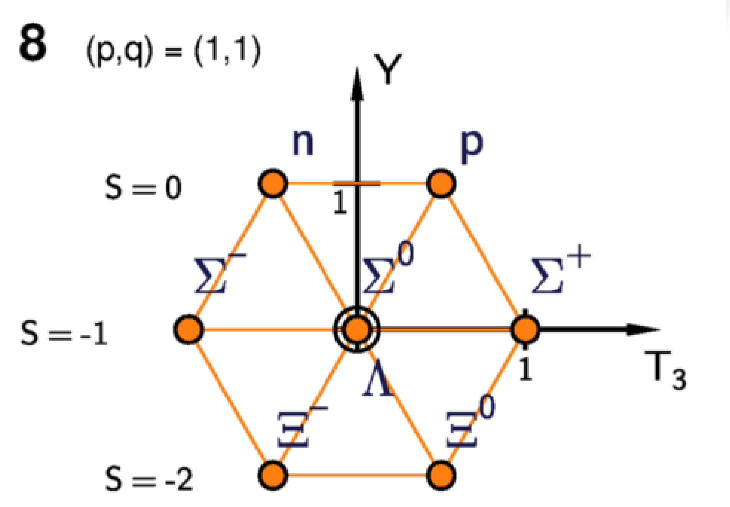
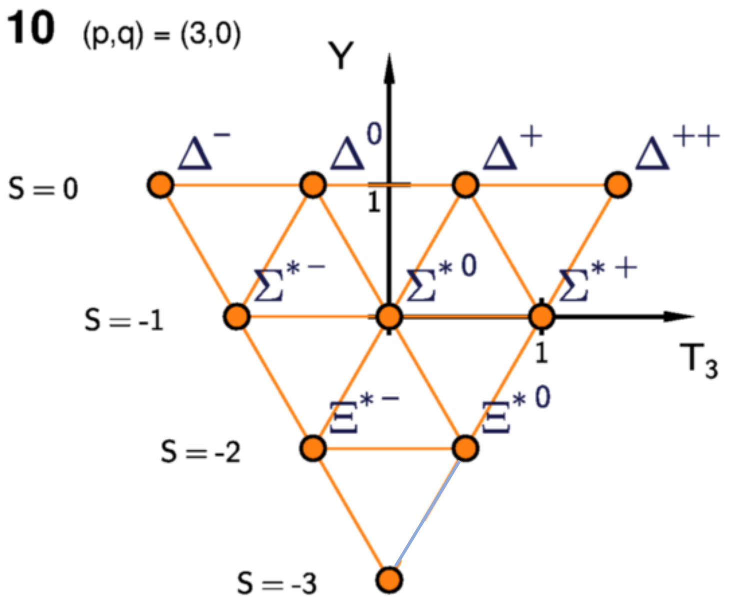
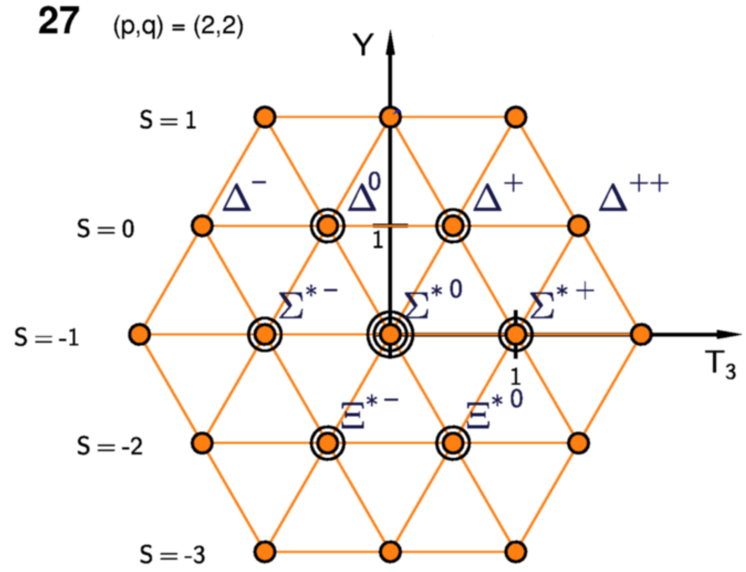
The Baryons

- The baryon multiplet organization was impressive, but the success of the idea was assured when the missing state strangeness -3 state in the baryon decuplet, the Ω^-, was found at Brookhaven







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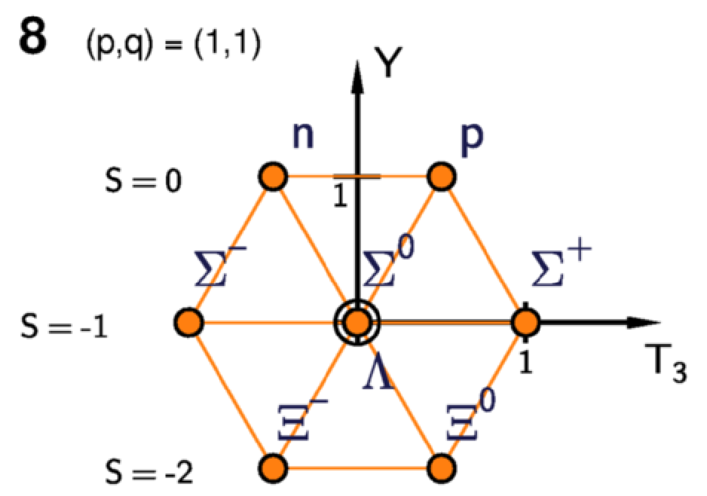
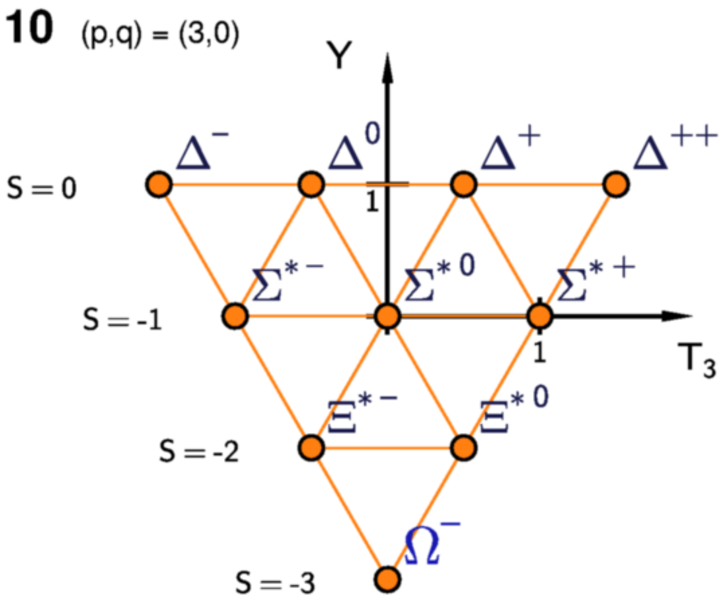
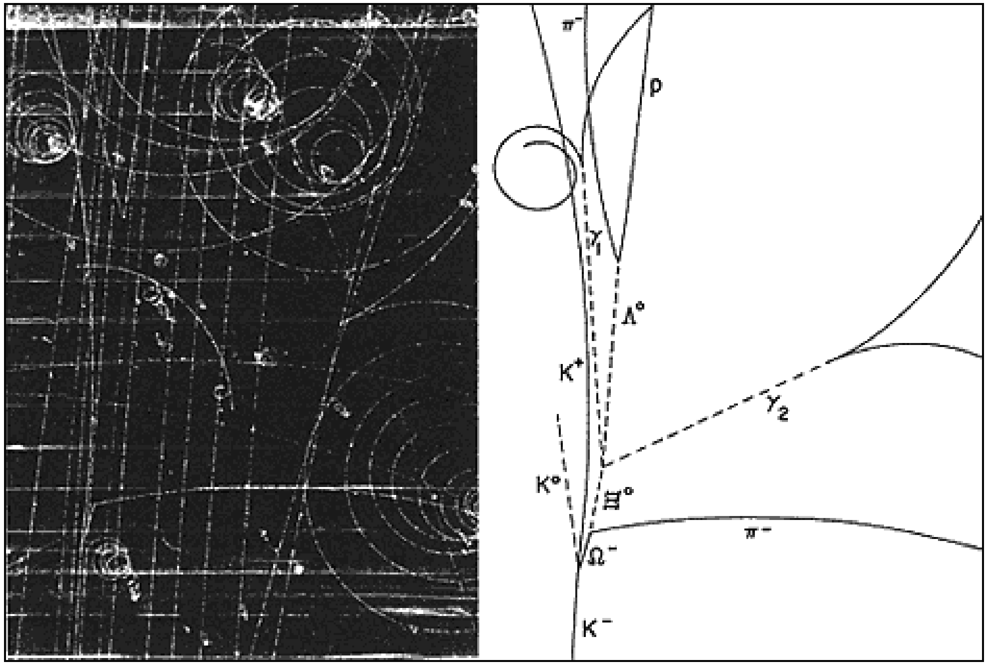
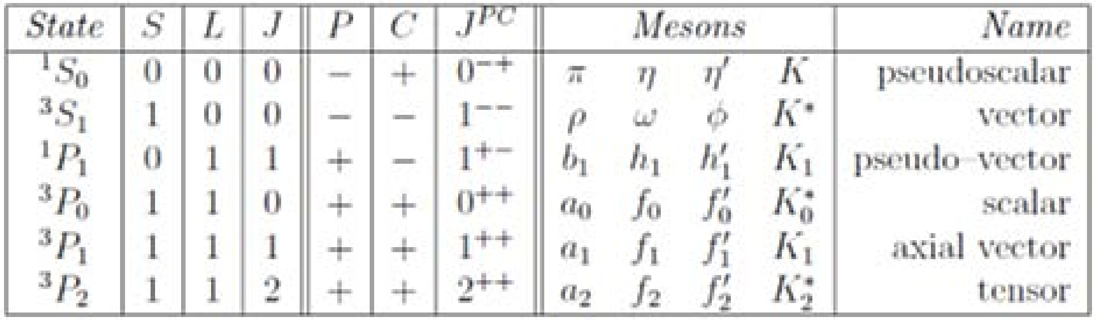




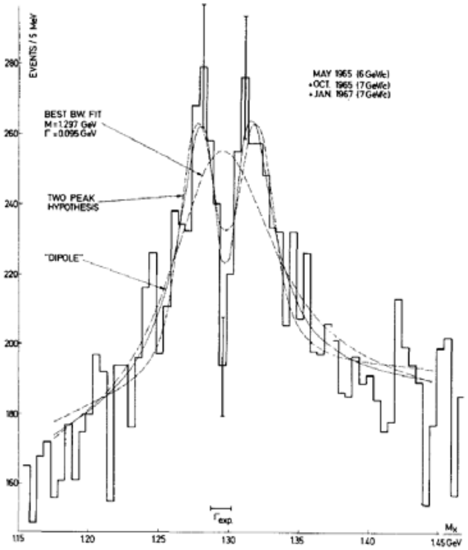


Bumps along the way

- The burgeoning success of the Eightfold Way was challenged by two CERN experiments (The MMS missing mass spectrometer ($\pi^+ p \rightarrow \pi^+ X^-$) and CERN Boson Spectrometer) that found that the a_2(1320) $J^{PC}=2^{++}$ meson, which was part of the $^3P_2$ SU(3) nonet, was in fact **two states**



State	S	L	J	P	C	J^{PC}	Mesons				Name
$^1S_0$	0	0	0	$-$	$+$	0^{-+}	π	η	η'	K	pseudoscalar
$^3S_1$	1	0	0	$-$	$-$	1^{--}	ρ	ω	ϕ	K^*	vector
$^1P_1$	0	1	1	$+$	$-$	1^{+-}	b_1	h_1	h'_1	K_1	pseudo-vector
$^3P_0$	1	1	0	$+$	$+$	0^{++}	a_0	f_0	f'_0	K^*_0	scalar
$^3P_1$	1	1	1	$+$	$+$	1^{++}	a_1	f_1	f'_1	K_1	axial vector
$^3P_2$	1	1	2	$+$	$+$	2^{++}	a_2	f_2	f'_2	K^*_2	tensor



- **There was no way to accommodate an extra state in the multiplet**
- An intense controversy ensued, extending over four years, with additional experiments, in several decay channels including bubble chambers. confirming the split and others showing a single state
- By 1972, the split had disappeared

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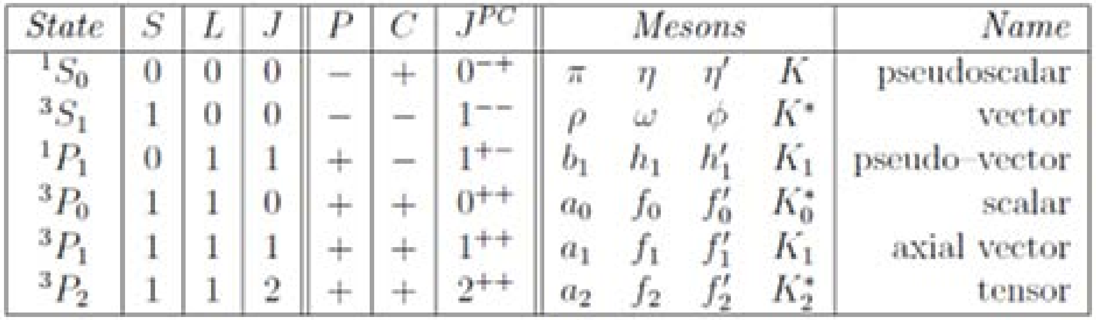

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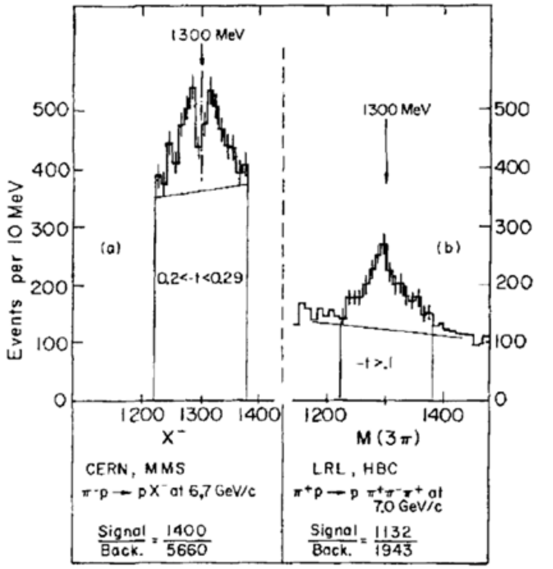

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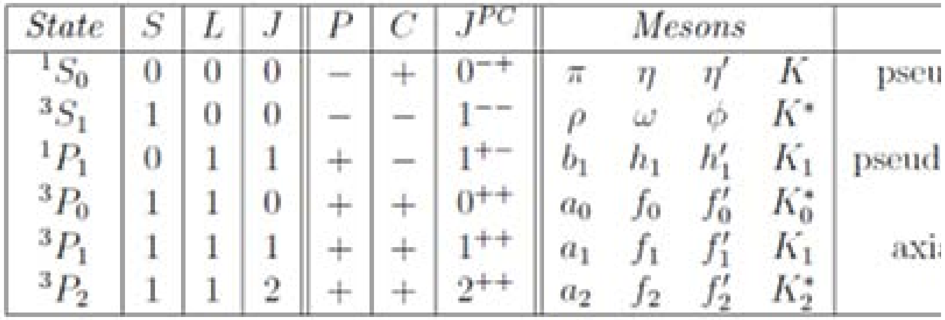

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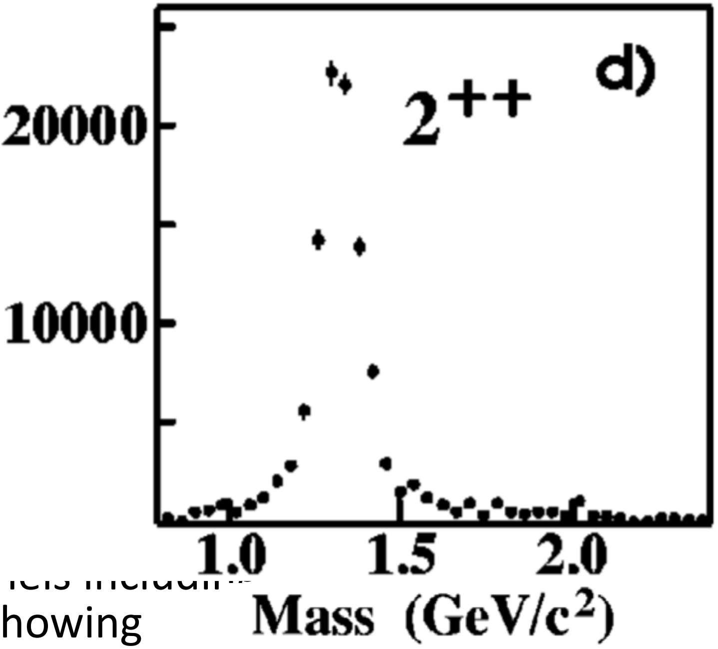

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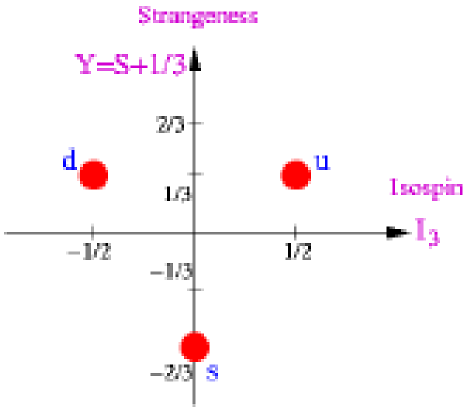
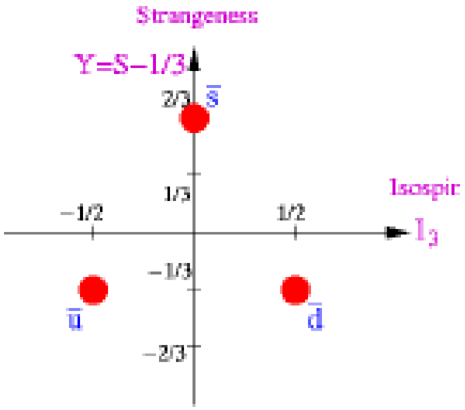
Quarks

- In 1964 Gell-Mann and Zweig independently conceived the idea that the elements of the fundamental representation of SU(3 could be combined to produce all the meson and baryon structures of the Eightfold Way
- mesons were $q\bar{q}$ states, baryons were qqq states

quark	charge Q [*e*]	isospin $\|I, I_3>$	Strange-ness S
up (u)	+2/3	$\|½, +½>$	0
down (d)	-1/3	$\|½, -½>$	0
strange (s)	-1/3	$\|0, 0>$	-1

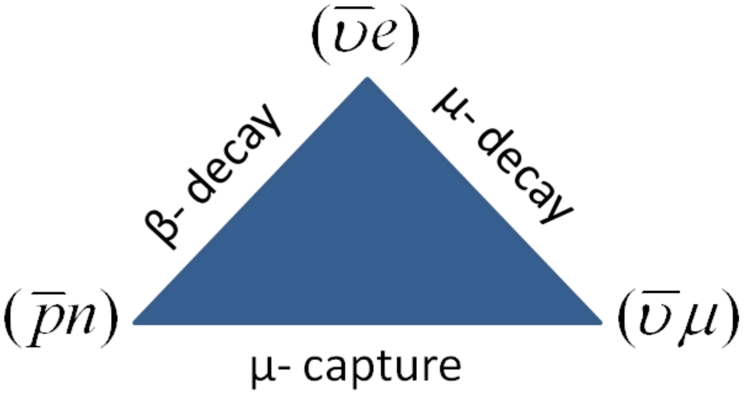




- MIB has covered the quark/parton DIS story

The weak current and the quest for the UFI

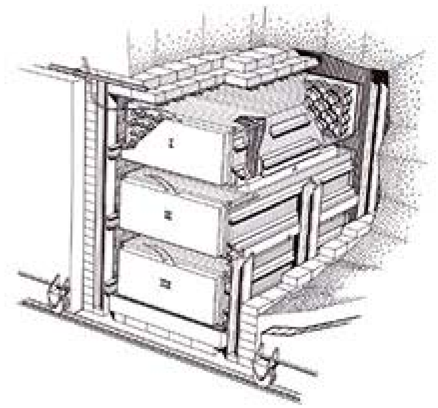
- The Fermi (vector) theory of weak decays of 1933 had been generalized to incorporate all possible Lorentz-invariant couplings (V, A, S, T, P)
  - Most experiments studied rates and angular correlations in nuclear β decay
  - Nuclear transitions could be classified into selection rules for allowed, forbidden, … transitions, on the basis of spin-parity changes
    - Fermi (V, S) or Gamow-Teller (A, T) ($P \rightarrow 0$ in the non-relativistic limit)
    - Conservation of parity was, of course, assumed
  - The Michel spectrum in μ decay and the rate of muon capture were soon measured
- The universality of the weak interactions was codified in the Puppi Triangle, as the **Universal Fermi Interaction**
- In modern language, this says that the charged current weak couplings of the electron, muon and up/down quarks are all mediated by the same force carrier, the W boson

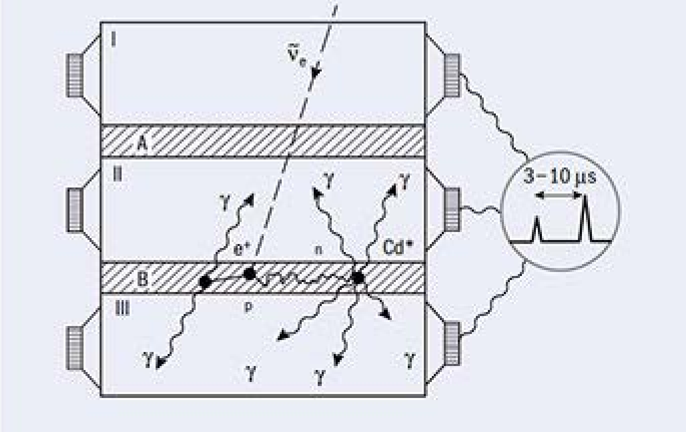


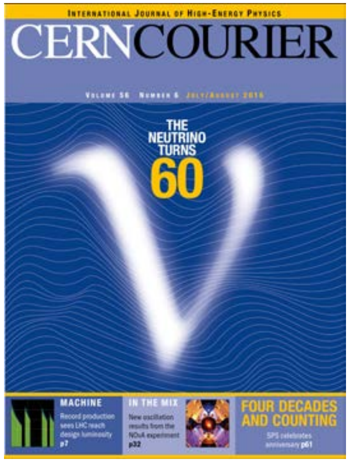
B. Pontecorvo, Phys. Rev. 72 (1947) 246
G. Puppi, Nuovo Cimento 5 (1948) 587

The discovery of the neutrino

- Pauli’s neutrino idea saved important conservation laws, but it remained to actually detect a neutrino
- In the context of a universal weak interaction, Bethe and Peierls calculated the cross-section for the inverse reaction $\overline{\nu}\, p \rightarrow e^{+} n$ to be ~6x10^{-44} cm. This seemed impossibly small
- In the ’50s, neutron-rich isotopes produced by fission in a nuclear reactor were recognized to be a copious source of beta decays, producing enormous numbers of antineutrinos
- Reines and Cowan built a detector at the Savannah River reactor to utilize the inverse beta-decay reaction using 300 liters of liquid scintillator with added cadmium chloride, viewed by 90 photomultiplier tubes
- The signal was a difference in delayed coincidence events recorded with the reactor on (2.88±0.22 counts/hour) and off (a factor of 20 less)







The θ-τ puzzle

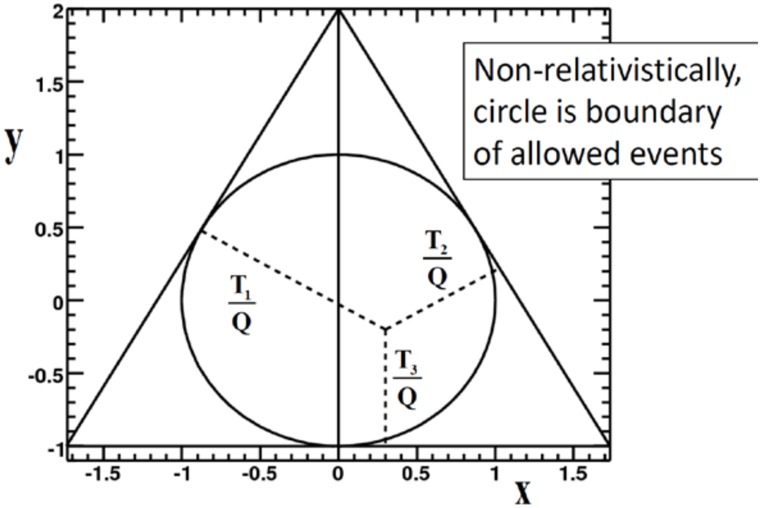
- In the early fifties, two particles of the same mass (~500 MeV) and lifetime were found to decay to states of differing parity:

The pion has J^P ($spin^{parity}$) 0^-, therefore

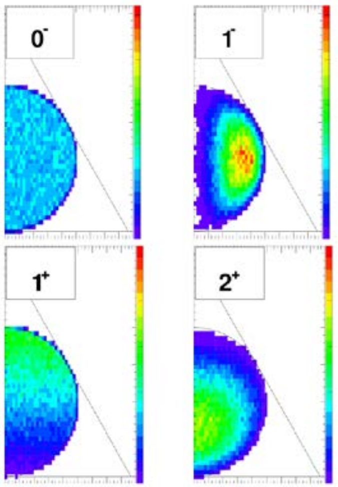
$$\theta^+ \to \pi^+\pi^0,\ \theta^0 \to \pi^+\pi^- \qquad m = 971 m_e \qquad J^P = 0^+$$

$$\tau^+ \to \pi^+\pi^+\pi^- \qquad m = 971 m_e \qquad J^P = 0^-$$

?



Non-relativistically, circle is boundary of allowed events



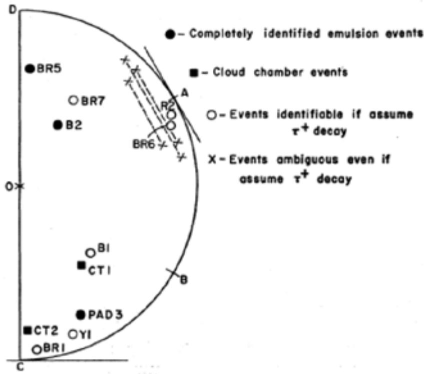


Fig. 3. The data on τ-meson decay events in which the signs of π-meson charges are established.

- A review of the literature* by Lee and Yang turned up no experimental evidence for the conservation of parity in the weak interactions. They proposed several tests to isolate a parity-violating pseudoscalar observable

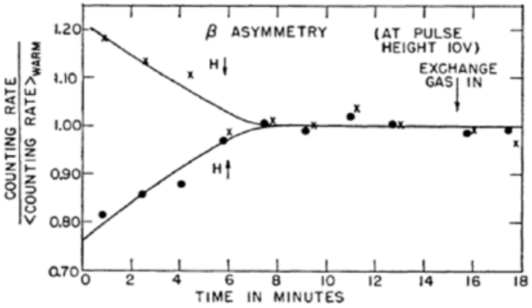
Parity (P) is not conserved (nor is C)

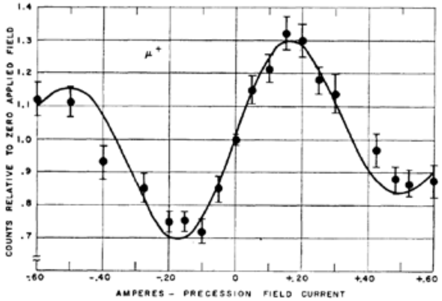
- Within months, three experiments found convincing evidence for the **maximal violation** of parity symmetry in the weak interactions

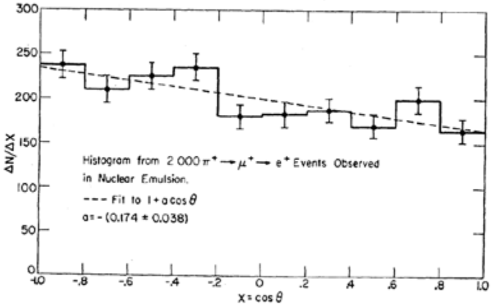
Electrons from β decay of ^{60}Co are polarized

Muons from pion decay are polarized, as shown by the asymmetry of decay electrons

$$\pi^+ \to \mu^+ + \nu,$$
$$\mu^+ \to e^+ + 2\nu$$







C.S. Wu, E. Ambler, R.W. Hayward, D.D. Hoppes and R.P. Hudson
(received January 15, 1957)

Phys. Rev. **105**, 1413 (1957)

Asymmetry is negative

$\alpha \simeq -0.4$ at $v/c \approx 0.6$

R.L. Garwin, L.M. Lederman and M. Weinrich
(received January 15, 1957)

Phys. Rev. **105**, 1415 (1957)

Fit to $1 - a\cos\theta$

If polarization is complete,

$a = -0.33 \pm 0.03$

J.I. Friedman and V.L. Telegdi
(received January 17, 1957)

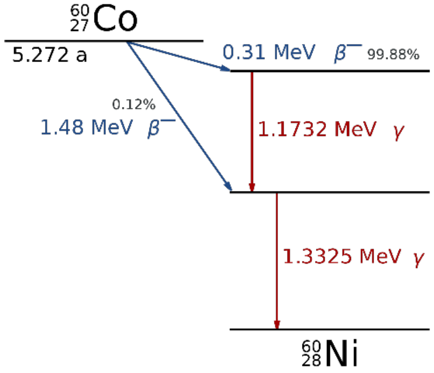
Phys. Rev. **105**, 1681 (1957)

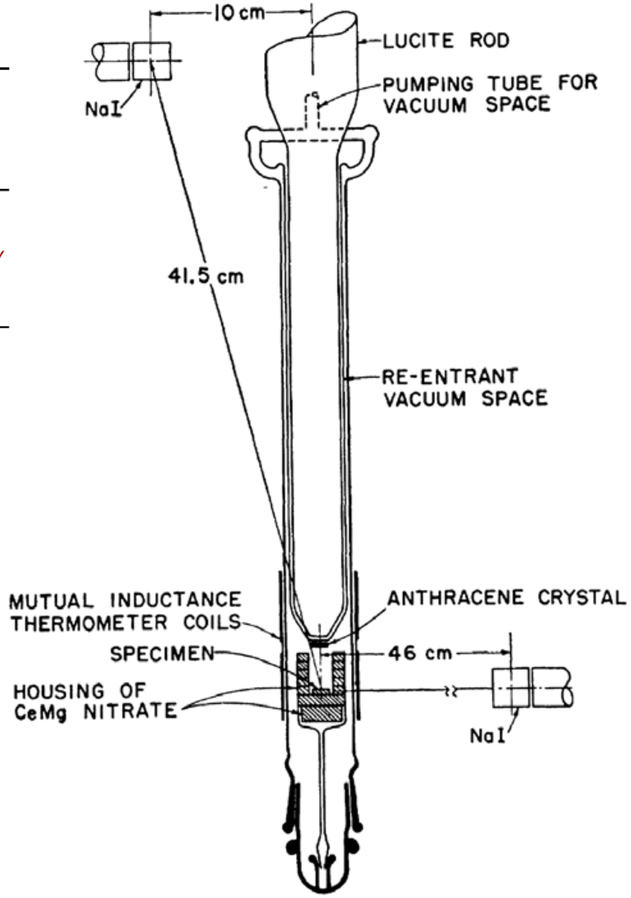
From 1300 events

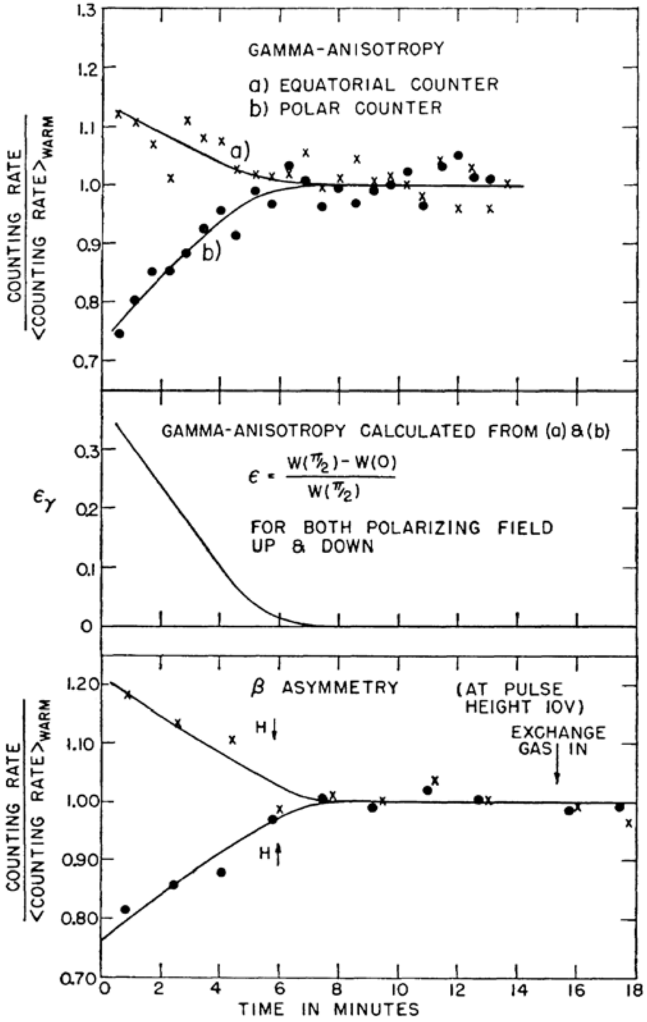
$$\left\{ \int_{90^\circ}^{180^\circ} |W(\theta)|\, d\Omega - \int_0^{90^\circ} |W(\theta)|\, d\Omega \right\} \Big/ \int_0^{180^\circ} W(\theta) d\Omega = 0.062 \pm 0.027$$

[4] *Note added in proof.* – From 2000 events, we get … 0.091±0.022.

The ^{60}Co experiment







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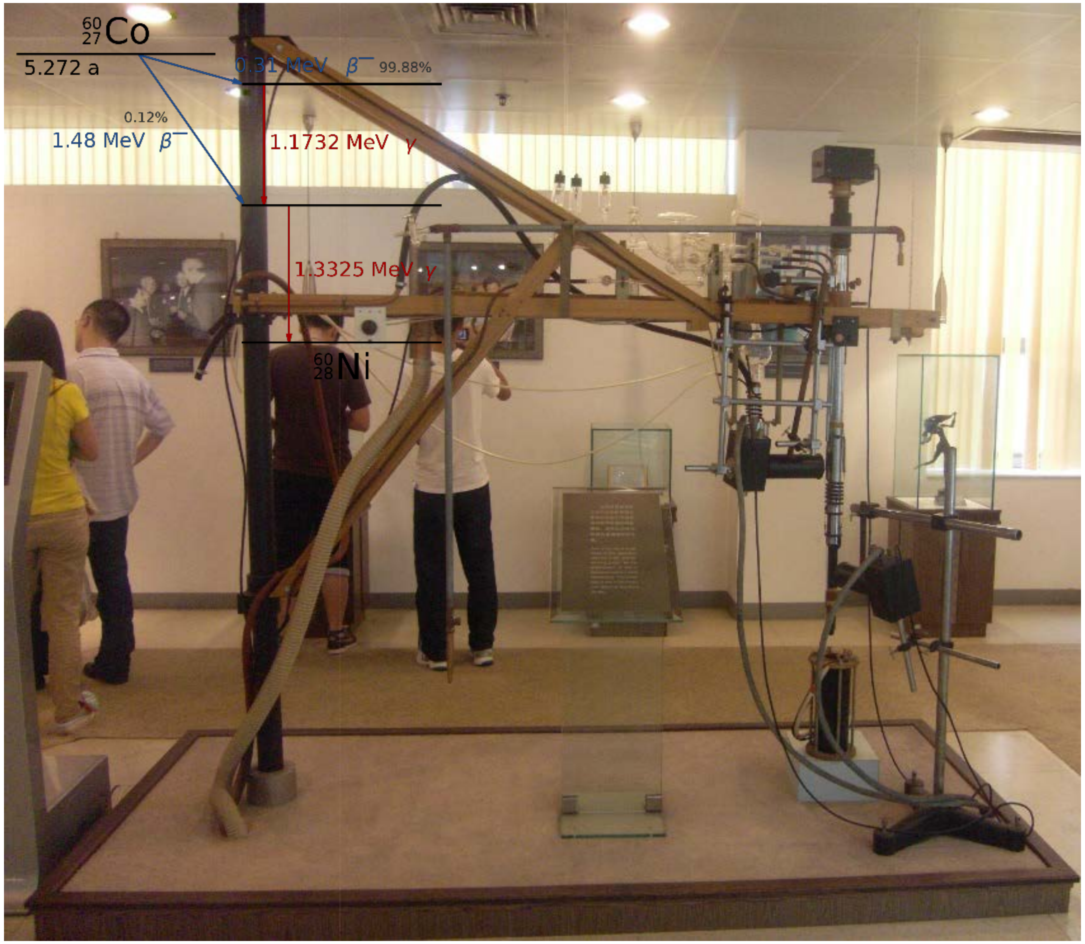
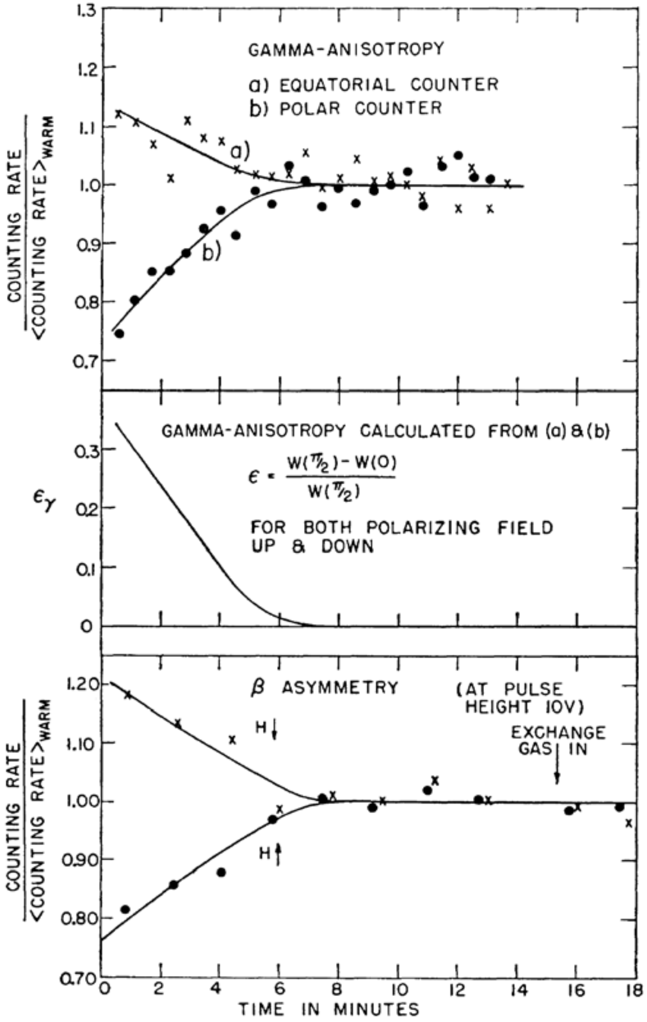
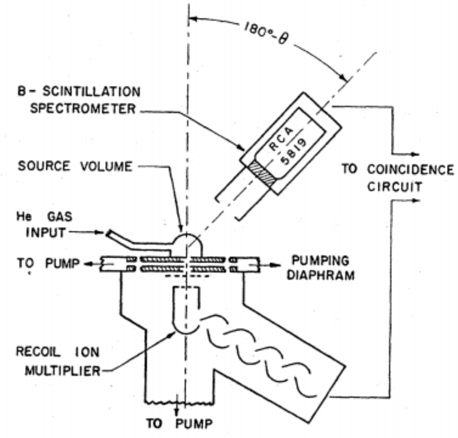


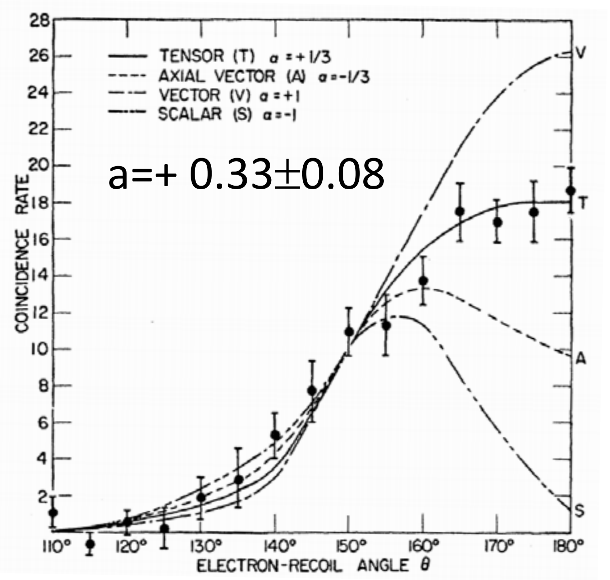


The two component neutrino theory and UFI

- Lee and Yang proposed a two-component theory of (massless) neutrinos to explain parity and charge conjugation non-conservation (sent to Phys. Rev. on Jan 10, 1957, revised on Jan 17). (the Wu and Lederman papers were sent on Jan 15)
- With the further assumption of lepton number conservation, the two component theory requires V and A couplings in muon decay and a ν_L
- The ^{60}Co pure ($5^+ \rightarrow 4^+$) Gamow-Teller β asymmetry could be explained by a T interaction with a ν_R, or an A interaction with a ν_L
- There was strong evidence, dating to 1953, from angular correlations in the e^--^{6}Li recoil distribution that the coupling in the Gamow-Teller decay $^6\text{He} \rightarrow {}^6\text{Li}\, e^- \nu$ was T .

B.M. Rustad and S.L. Ruby,
Phys. Rev. **89**, 880 (1953);
ibid Phys.Rev. **97**, 991 (1955)



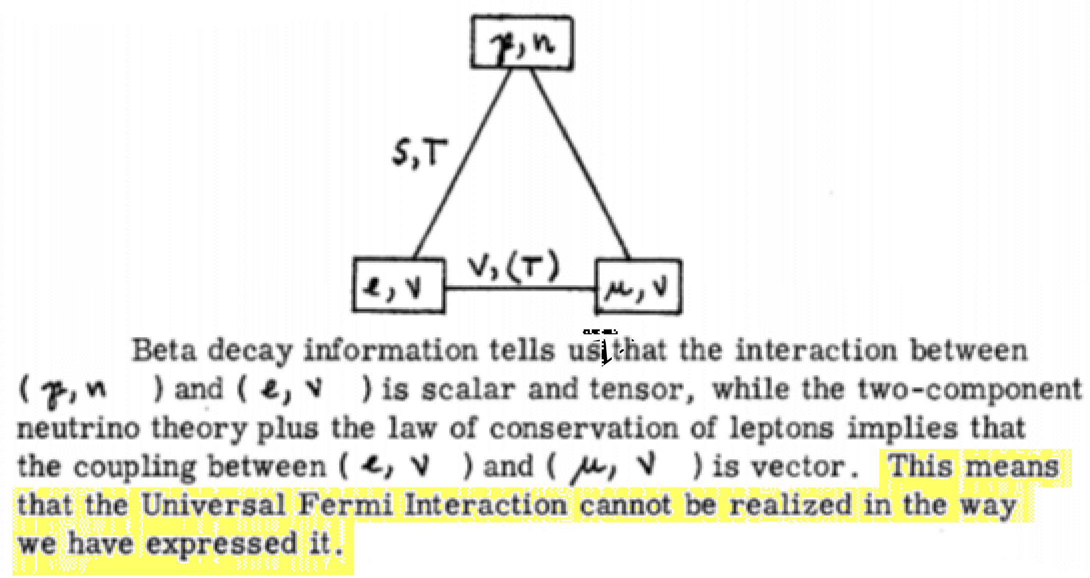


a=+ 0.33±0.08

- Other β decay experiments preferred S coupling
- The two component theory and/or the idea of a Universal Fermi Interaction were in trouble

The two component neutrino theory and UFI

- At the 1957 Rochester Conference, T.D. Lee reviewed the evidence:

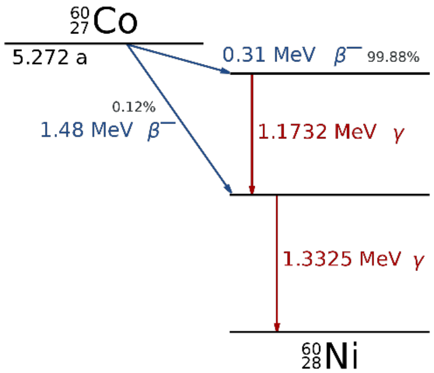


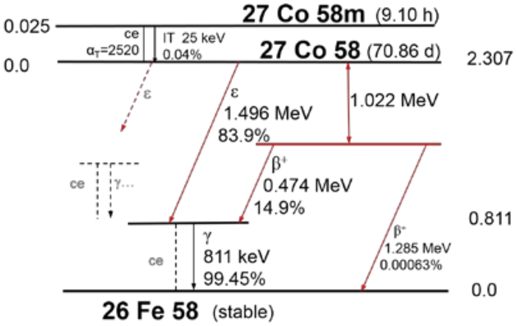
Beta decay information tells us that the interaction between (p, n) and (e, ν) is scalar and tensor, while the two-component neutrino theory plus the law of conservation of leptons implies that the coupling between (e, ν) and (μ, ν) is vector. This means that the Universal Fermi Interaction cannot be realized in the way we have expressed it.

- At the same conference Wu discussed her second asymmetry experiment
- Is perhaps ironic that the idea of a UFI survived (hence the Standard Model), while the massless neutrino did not quite

^{58}Co casts doubt on S, T coupling

- There was a second Co β decay experiment using the same apparatus





E. Ambler, R.W. Hayward, D.D. Hoppes, R.P. Hudson and C.S. Wu

Phys. Rev. **106**, 1361 (1957)

- ^{58}Co also showed a parity-violating asymmetry

$$\alpha \simeq +0.11 \text{ at } v/c \approx 0.6$$

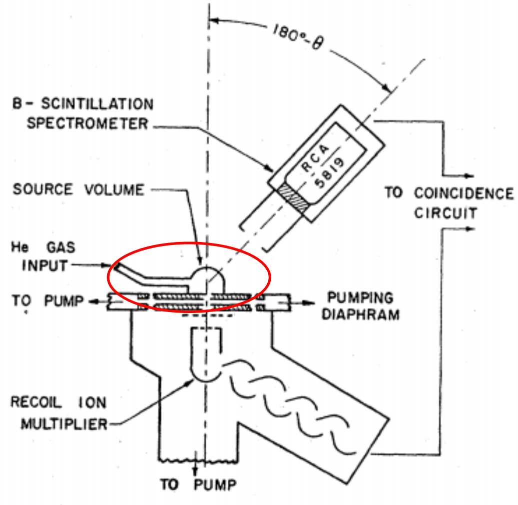
in the ^{58}Co $2^+ \rightarrow 2^+$ β^+ transition, which is a mixed Fermi/Gamow-Teller decay

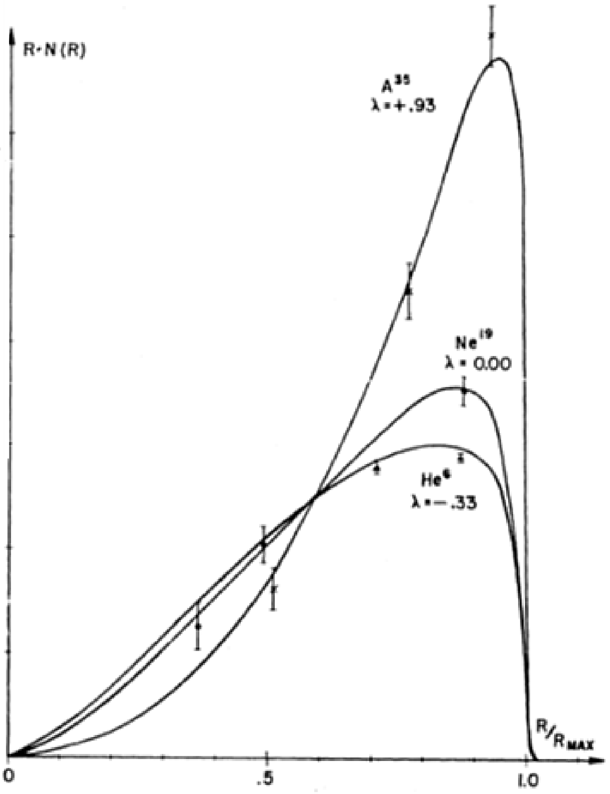
  - This value is consistent with the two neutrino hypothesis **if** the Fermi matrix element is negligible, but the ratio of M_F/M_{GT} was known (1/8); this value still leads to a positive asymmetry, but one nearly as large as that for ^{60}Co

- Taking this discrepancy seriously, Wu then proposed a complete re-examination of previous experiments, including ^{6}He, and the investigation of the asymmetry in pure GT ^{35}Ar decay

Problems with ^{6}He and new experiments

- Wu and Schwarzshild undertook a detailed study of the Rustad, Ruby apparatus (this was published only as a Columbia preprint)
- They demonstrated (building a 10x model of the gas volume) that the detected ^{6}He decays originated not only from the expected decay volume, but also from the inlet pipe
  - Thus the inferred β-ion angle was incorrect in a significant number of cases

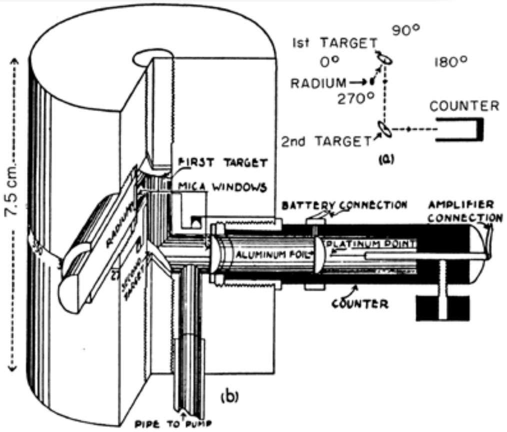


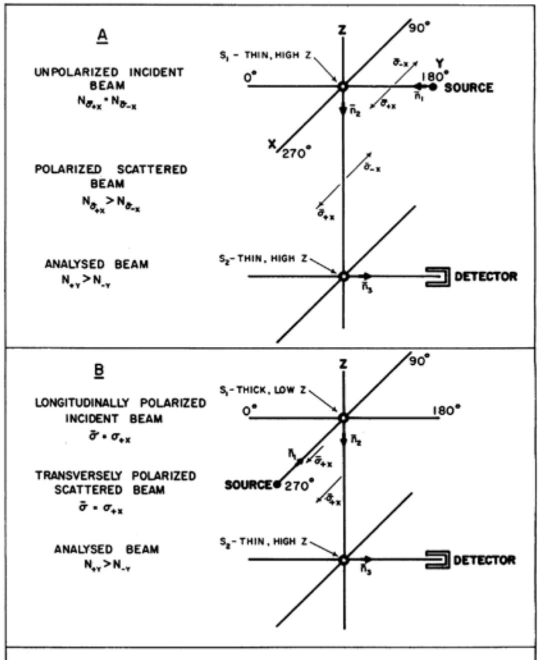


- A new series of experiments on ^{6}He, ^{19}Ne and ^{35}Ar, that detected only the recoil, by W.B. Hermannsfeldt, R.L. Burman, P. Stähelin, J.S. Allen and T.H. Braid, Phys. Rev. Lett. **1**, 61 (1958) produced excellent agreement with the V, A hypothesis
- These were soon joined by a host of new β decay measurements and measurements of the polarization of electrons in β decay that settled the issue

* The non-discovery of non-conservation of parity

- Cox, McIlwraith and Kurrelmeyer (1928) and later Chase (1930) searched for the polarization of double-scattered electrons which had been predicted by Mott using the new attribute of electron - spin
  - They did not find the Mott asymmetry, as the experiment used thick scattering foils and had too much background, but **they did find an asymmetry in the scattered electron distribution that violated parity symmetry**
- This result was hardly noticed
  - The idea of parity conversation was not central to mainstream concerns
- From a modern perspective, the effect they saw was evidence that the electron beam, produced by β decay, was polarized, with higher energies having higher polarization. The effect was more pronounced when the electron spectrum was hardened
- **This is evidence of violation of parity in β decay**
- In an interesting coda, many years later Grodzins pointed out that the sign of the measured parity-violating asymmetry in these experiments was wrong
  - Forensic studies have not yielded an explanation



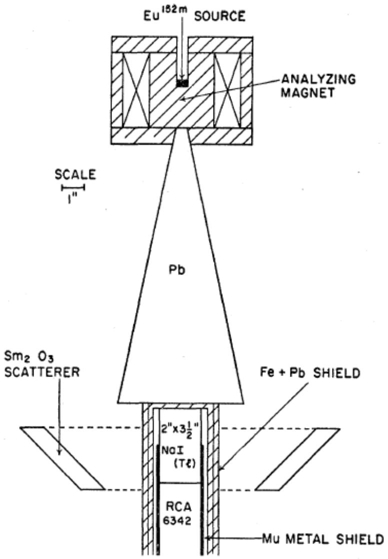


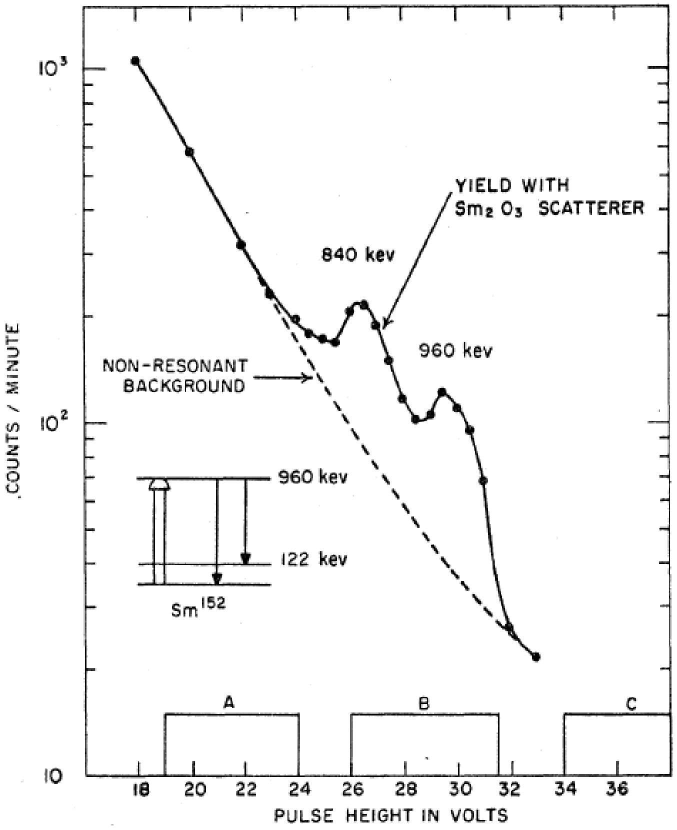
DOUBLE SCATTERING EXPERIMENTS - ROTATING SOURCE, FIXED DETECTOR

Helicity of the neutrino

- Goldhaber, Grodzins and Sunyar (Phys.Rev. **109,** 1015 (1958)) directly measured the helicity of the neutrino produced in electron capture in ^{152}Eu by utilizing resonant scattering to analyze the circular polarization of the resulting photon
- As the magnetic field was reversed there was a counting asymmetry

$$\delta = \frac{2(N_- - N_+)}{N_- + N_+} = +0.017 \pm 0.003$$

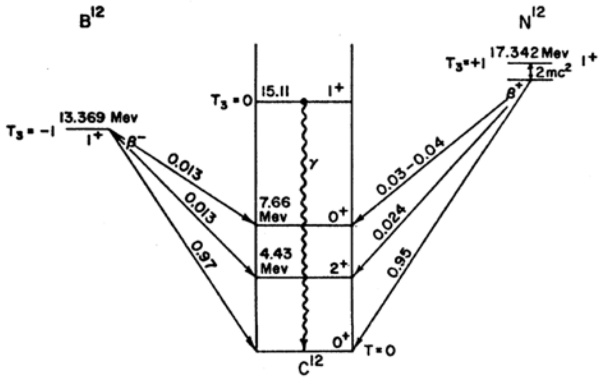




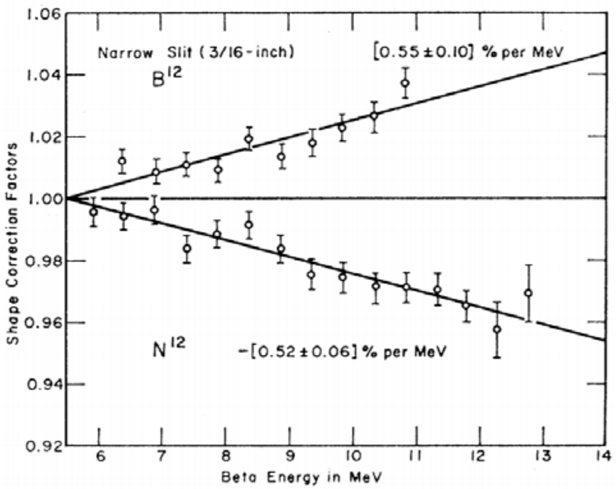
- The charged weak current is *V-A* and both the two component theory and UFI survived

Conserved vector current (CVC)

- In the presence of strong renormalization effects, why should weak decays of leptons and quarks have the same coupling constant, as embodied in the Universal Fermi Interaction?
- The success of the UFI idea is explained by the conserved vector current hypothesis (CVC) of Gerstein and Zel’dovich, and Feynman and Gell-Mann
- CVC relates the isovector electromagnetic form factors and the isovector weak form factors
- There are several direct experimental tests, among them the pion β decay rate, the relation of electron and neutrino scattering form factors, and the equivalence of the β spectra in the A=12 isovector triplet



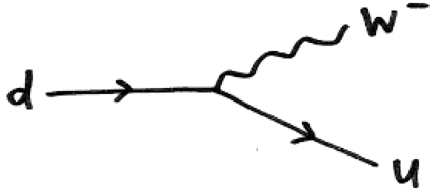
- There was also the question of PCAC, the partial conservation of the axial vector weak current in the soft-pion limit, which had a similarly fraught experimental and theoretical history

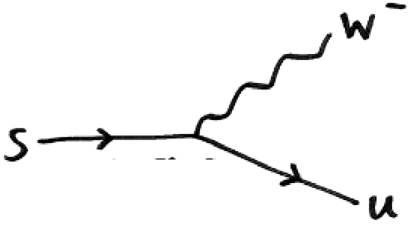


Y.K. Lee, L.W. Mo and C.S.Wu,
Phys. Rev. Lett. **10,** 253 (1963)

The Cabibbo Angle

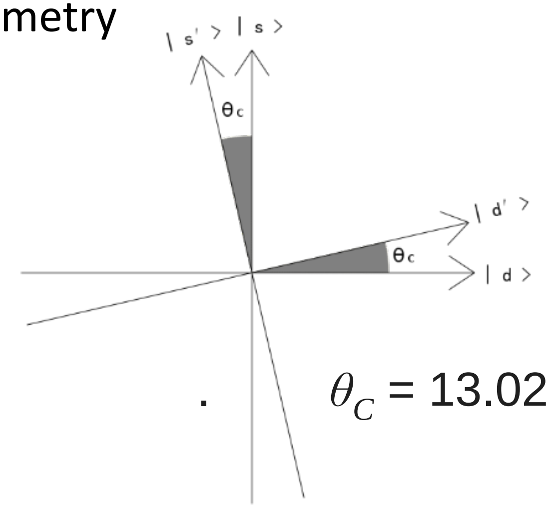
- No sooner had the idea of universal weak interactions taken hold, when it was found that the leptonic (weak) decay rates of the pion and kaon were quite different





- Universality was preserved, in 1963, with the introduction of the Cabibbo angle θ_c, which parametrized a new unitary symmetry
- Then,

$$\begin{bmatrix} d' \\ s' \end{bmatrix} = \begin{bmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{bmatrix} \begin{bmatrix} d \\ s \end{bmatrix}$$



The Cabibbo angle parameterizes the rotation of the mass eigenstates with respect to the weak eigenstates

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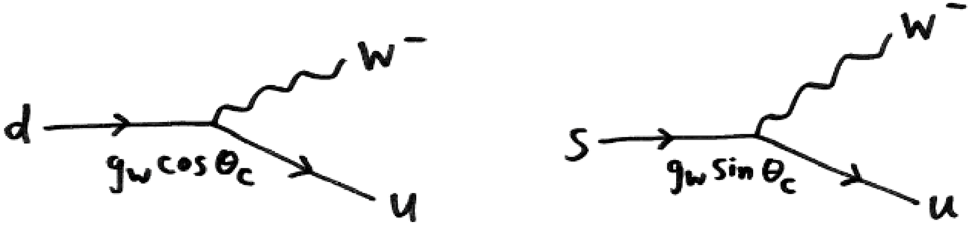

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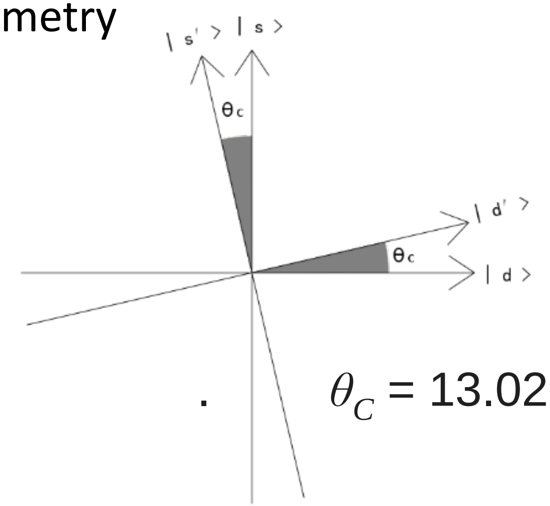

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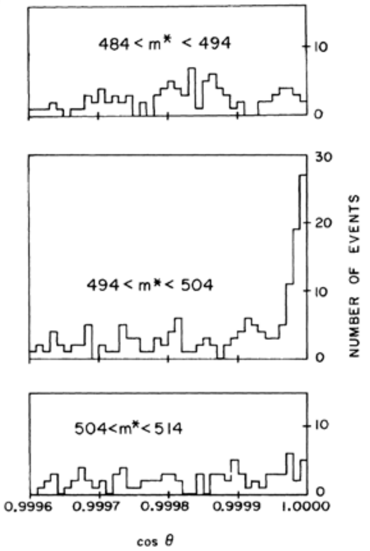
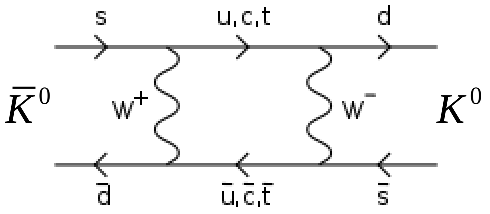
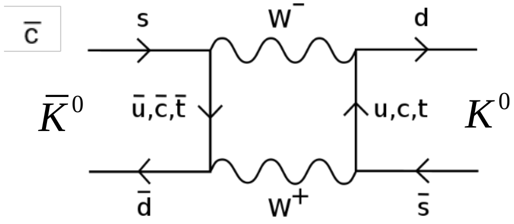
$\theta_C = 13.02°$

CP violation in K^0_L decay

- Although parity P was shown to be maximally violated in weak interactions, there was some comfort in the context of the CPT theorem, in that the CP transformation appeared to be intact
- This changed in 1964 when Cronin and Fitch showed that the long-lived neutral K meson could decay to $\pi^+\pi^-$ as well as to the dominant $\pi^+\pi^-\pi^0$ decay
  - These two states have opposite CP, so CP is not conserved in K_L decay. The violation is small: ~2x10^{-3}, not maximal as with P (and C)
  - CP violation in a neutral meson system can either be direct or indirect, due to the phenomenon of neutral meson mixing







  - The Cronin-Fitch experiment found indirect CPV, that is CPV in the interference of mixing and decay
  - In the ’90s, after an increasingly sensitive series of experiments at Fermilab and CERN, direct CPV was found in the K meson system
  - Due to large “hadronic uncertainties”, these measurements told us little about the underlying quark couplings. The special properties of the B meson system allow CPV measurements in B^0 decay to be cleanly interpreted in terms of fundamental quantities

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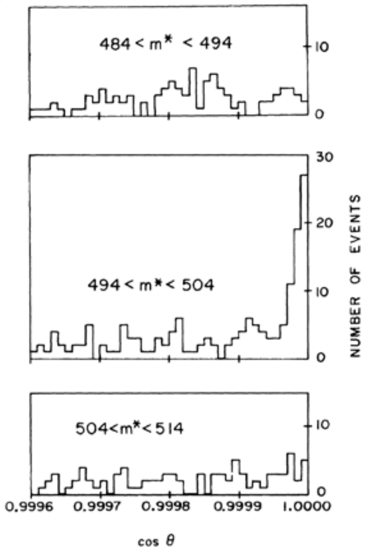

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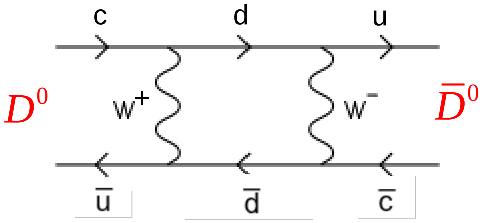

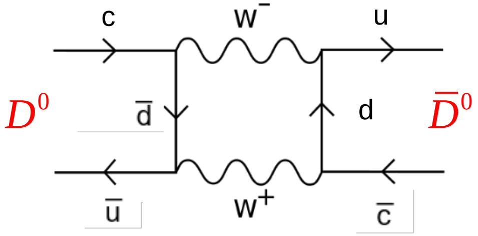

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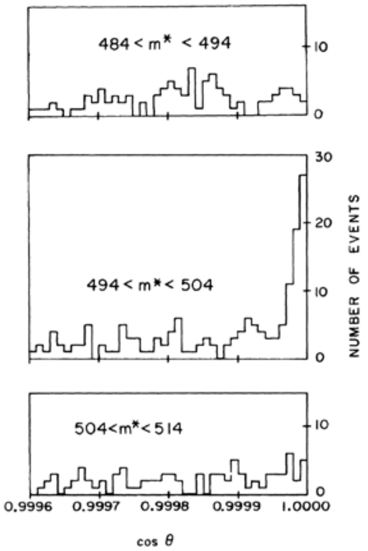

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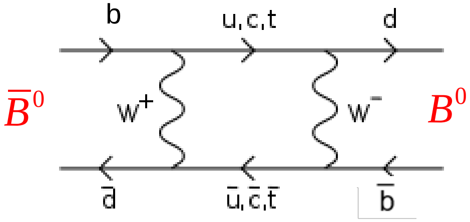

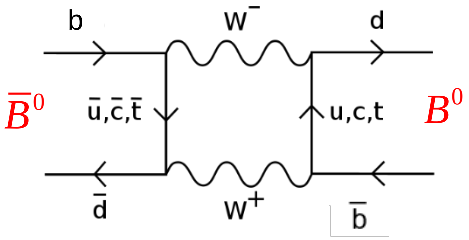

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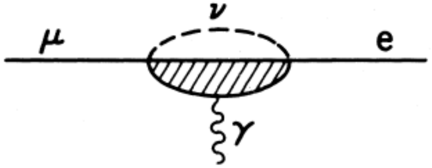
There's more than one kind of neutrino

- A mystery: why was the decay $\mu^- \to e^- \gamma$ not observed?
  - The answer led to the discovery of a new conserved quantum number: lepton flavor, which is shared by associated neutrinos
    - The electron and muon have different lepton flavor, so one cannot decay into the other, but if we associate **distinct neutrinos** with each charged lepton, then decays that conserve lepton flavor, such as $\mu^- \to e^- \bar{\nu}_e \nu_\mu$ can occur



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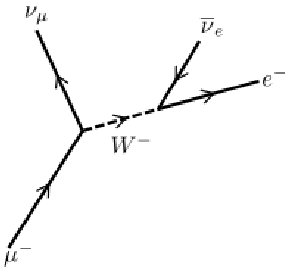
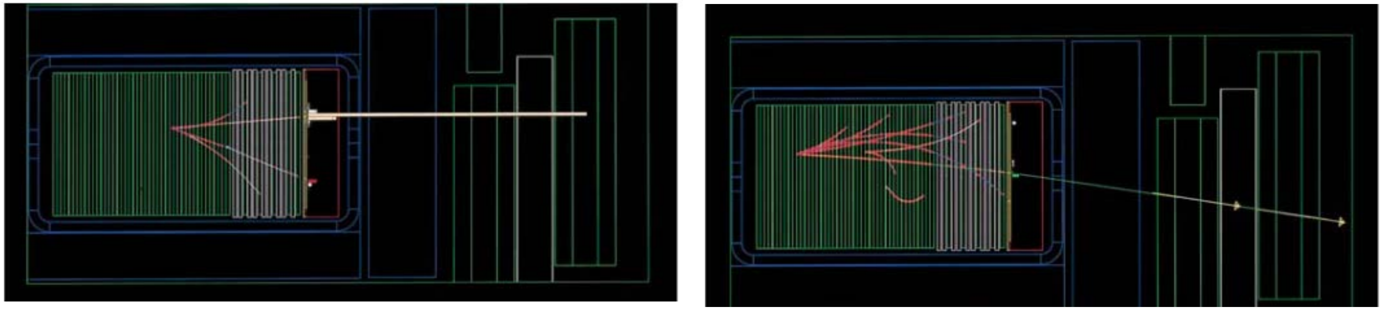


- This led to the first accelerator neutrino experiments (at the Brookhaven AGS and CERN PS)
  - Produce a beam of ν_μ from the decay of pions and kaons ($\pi \to \mu\nu_\mu , K \to \mu\nu_\mu$)
  - If there is indeed a ν_μ, then neutrino interactions should produce only muons



Lederman, Schwartz, Steinberger

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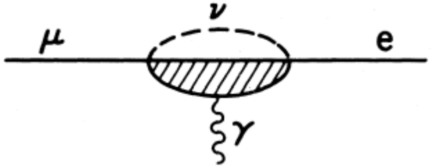

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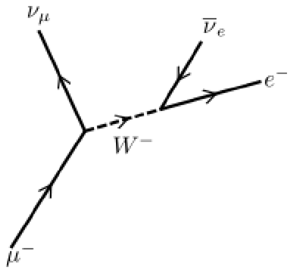

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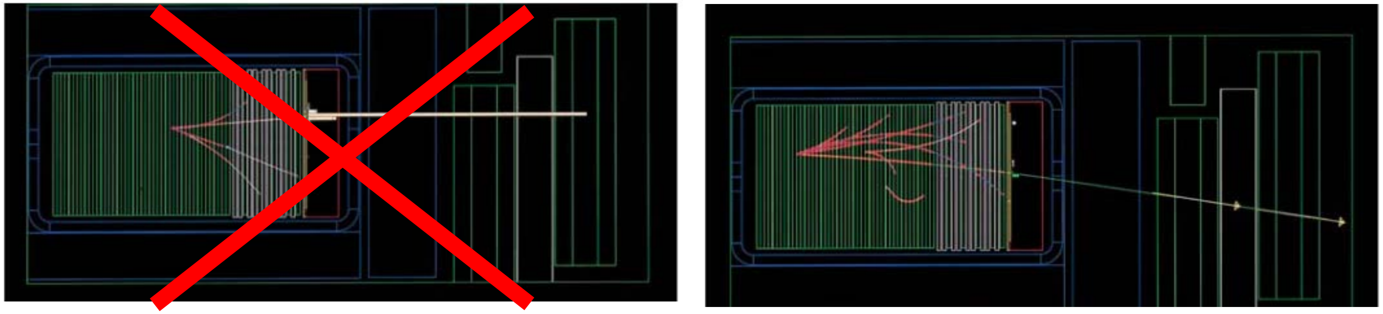

Lederman,
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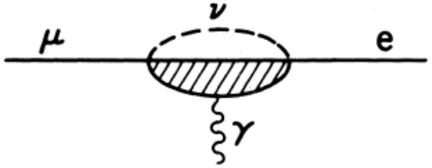

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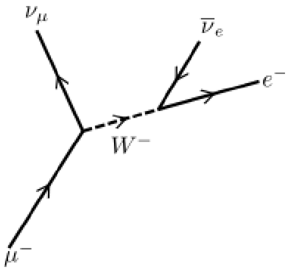

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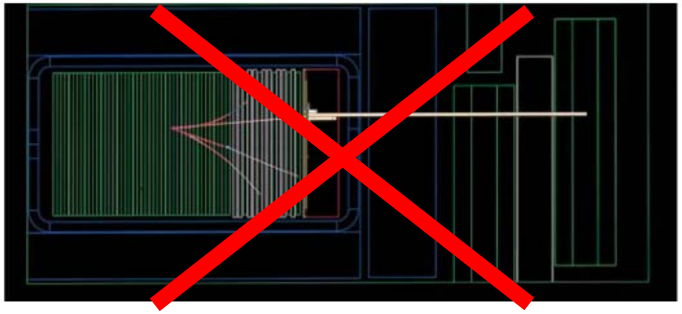
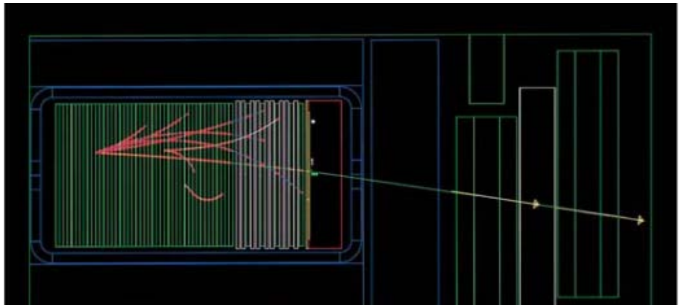




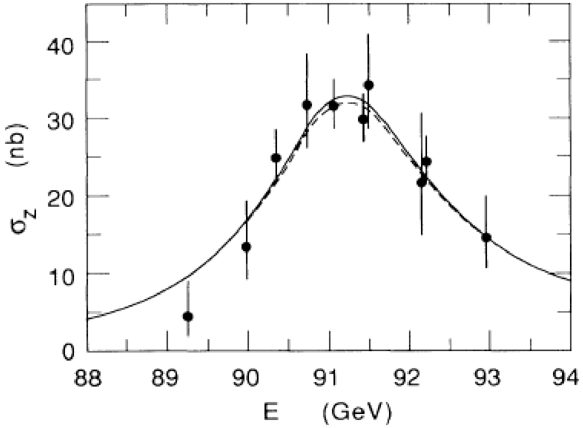
Lederman,
Schwartz,
Steinberger

The number of (light) neutrinos

- Since the coupling strength of the Z^0 is known in the Standard Model, the width of the Z^0 pole in e^+e^- annihilation is precisely predicted

$$\Gamma_Z = \Gamma_{hadrons} + \Gamma_{electrons} + \Gamma_{muons} + \Gamma_{taus} + N_\nu \Gamma_\nu$$

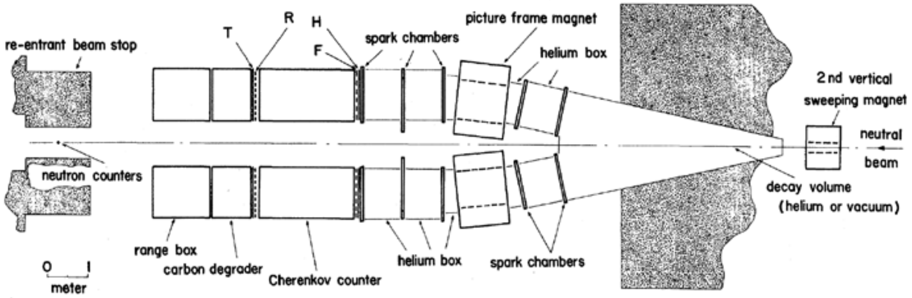
  - The Z^0 mass and decay width to visible modes were measured at the SLC in 1989, indicating $N_\nu = 2.8 \pm 0.6$. The four LEP detectors soon improved this substantially
  - The current PDG value is $N_\nu = 2.984 \pm 0.008$

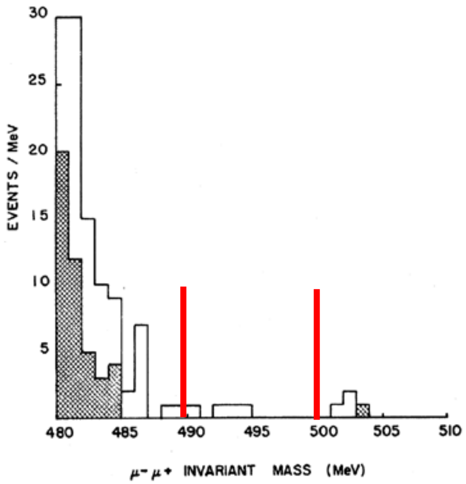


- The primordial abundance of helium also allows setting a limit on the number of neutrino species $N_\nu = 2.90 \pm 0.22$
- There are no more than three light neutrino species
  - We still don't know why
  - Persistent experimental anomalies leave room for the existence of "sterile" neutrinos, an active area of study

$K_L^0 \to \mu^+\mu^-$ and the unitarity limit

- Using the measured rate of $K_L^0 \to \gamma\gamma$ and unitarity, the branching fraction $K_L^0 \to \mu^+\mu^-$, a weak neutral current decay, is robustly predicted to be R=4.8 x 10^{-9} (Martin, de Rafael and Smith)
- In 1971 an LBL experiment (A. Clark, T. Eliof, R.C. Field, H.J. Frisch, R. P. Johnson, L.T. Kerth and W.A. Wenzel) found R < 1.82 x 10^{-9} @ 90% CL

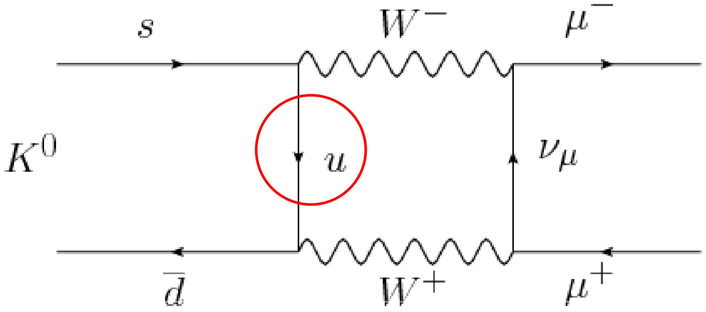




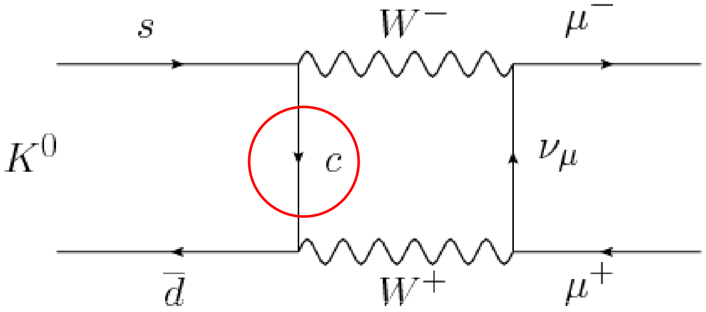
- Where were the neutral weak currents?

The GIM mechanism

- Murray Gell-Mann: “Anything that is not forbidden is mandatory”
- Flavor-changing neutral weak currents are allowed in a three quark (u,d,s) world
- However a sensitive search for the neutral current decay $K_L^0 \to \mu^+\mu^-$ didn’t find it



- The explanation put forward by Glashow, Iliopoulos and Maiani (GIM) was that there was another quark, the charmed quark, c, that engendered a cancellation:



- The GIM mechanism was theoretically persuasive, but where was the c quark?

Resolution matters

VOLUME 25, NUMBER 21 PHYSICAL REVIEW LETTERS 23 NOVEMBER 1970

Observation of Massive Muon Pairs in Hadron Collisions*

J. H. Christenson, G. S. Hicks, L. M. Lederman, P. J. Limon, and B. G. Pope
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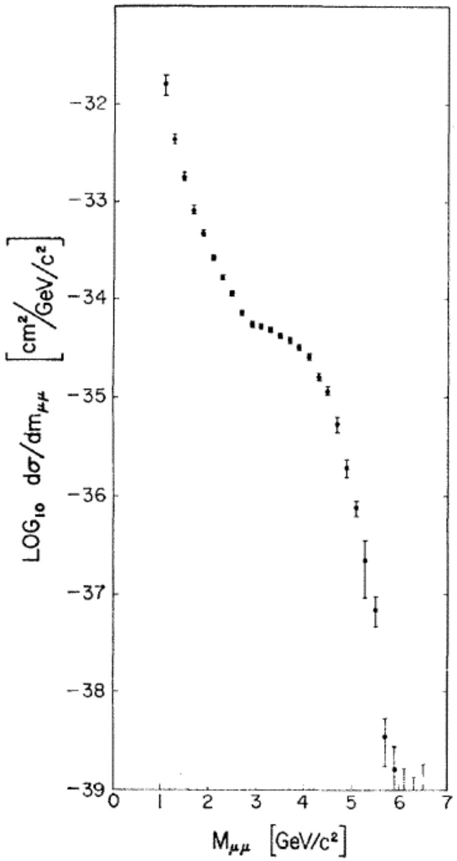
CERN Laboratory, Geneva, Switzerland

(Received 8 September 1970)

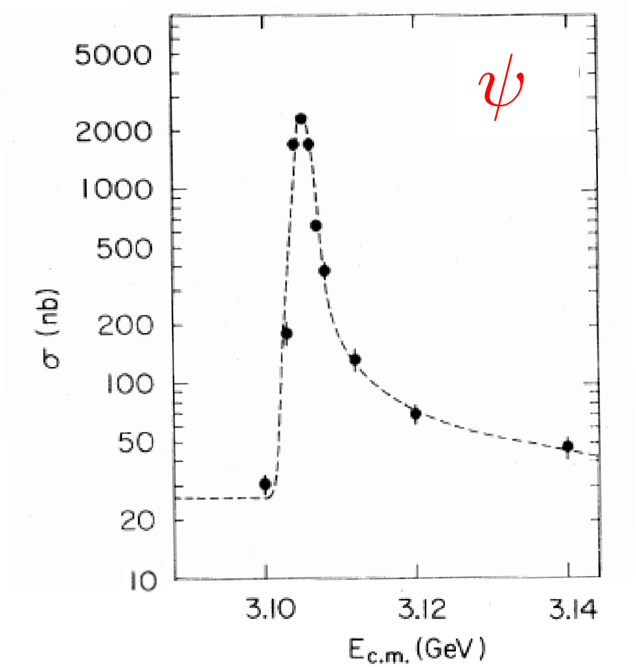


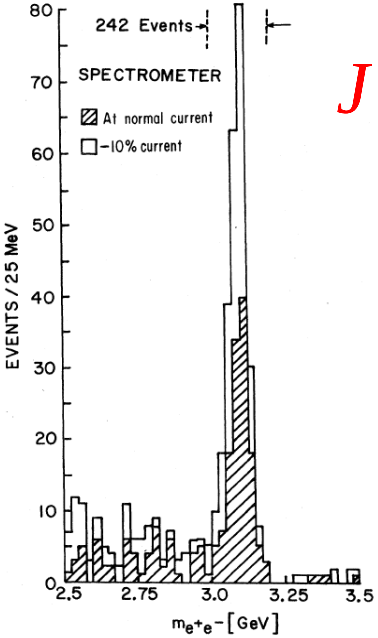
σ ~1 Gev at $m_{\mu\mu}$ = 3 GeV

" As seen both in the mass spectrum and the resultant cross section $d\sigma/dm$, there is no forcing evidence of any resonant structure."

The November revolution

- Two distinct experimental threads came together quite unexpectedly in November 1974 (*cf.* MIB)
  - The SPEAR magnetic detector group at SLAC was chasing down inconsistencies in their measurements of the energy dependence of the total cross section for $e^+e^-\rightarrow$hadrons
  - The Ting group at MIT was searching for massive vector mesons in proton collisions at the Brookhaven AGS

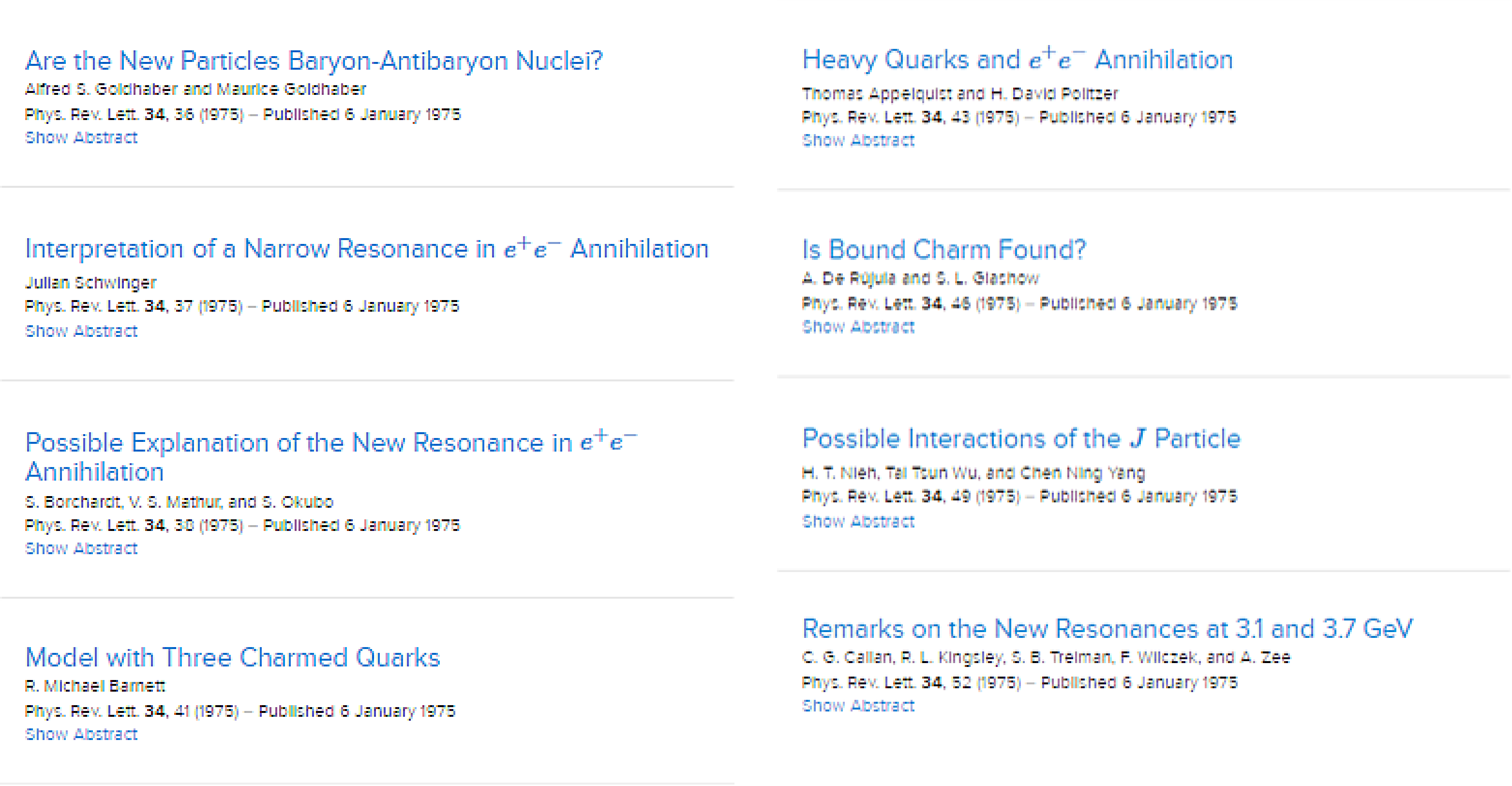




  - Both found a new, extremely narrow resonant state (the J/ψ) that could be produced by, and could decay into, electron-positron pairs. These papers were published instantly, as it was clear that this was something new and important

What was the J/ψ?

- This new narrow state was clearly important, but what was it?



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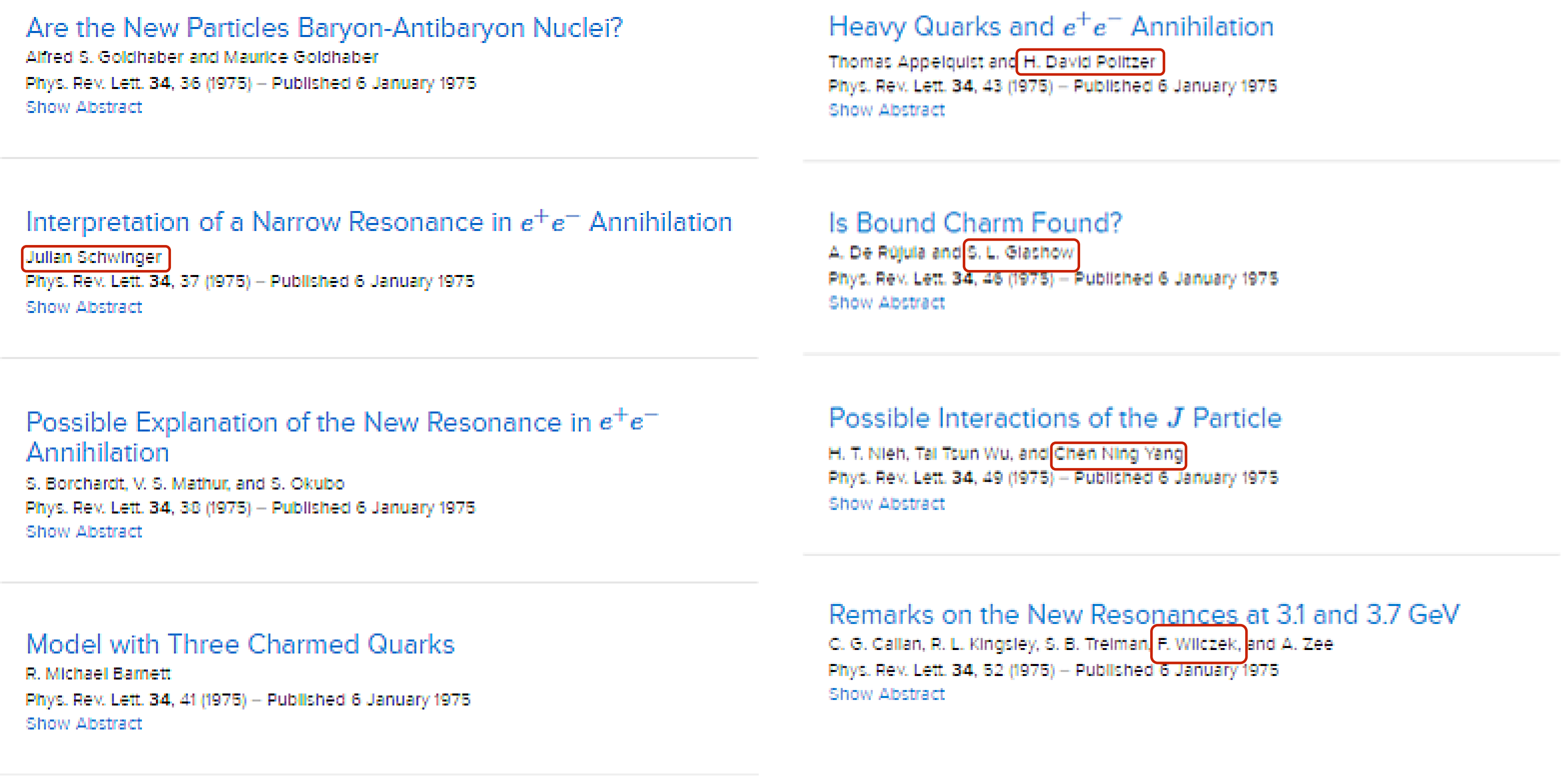

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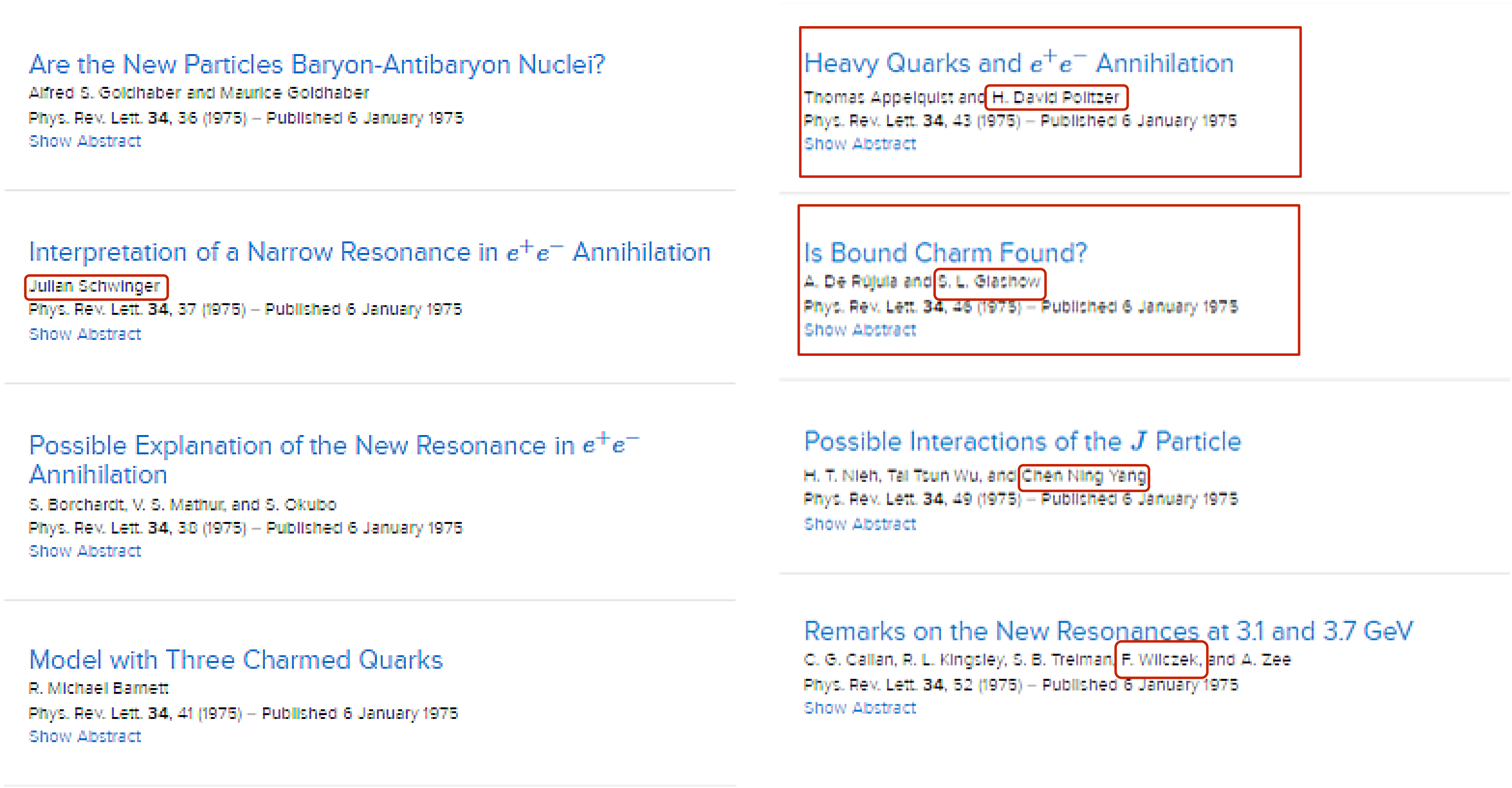

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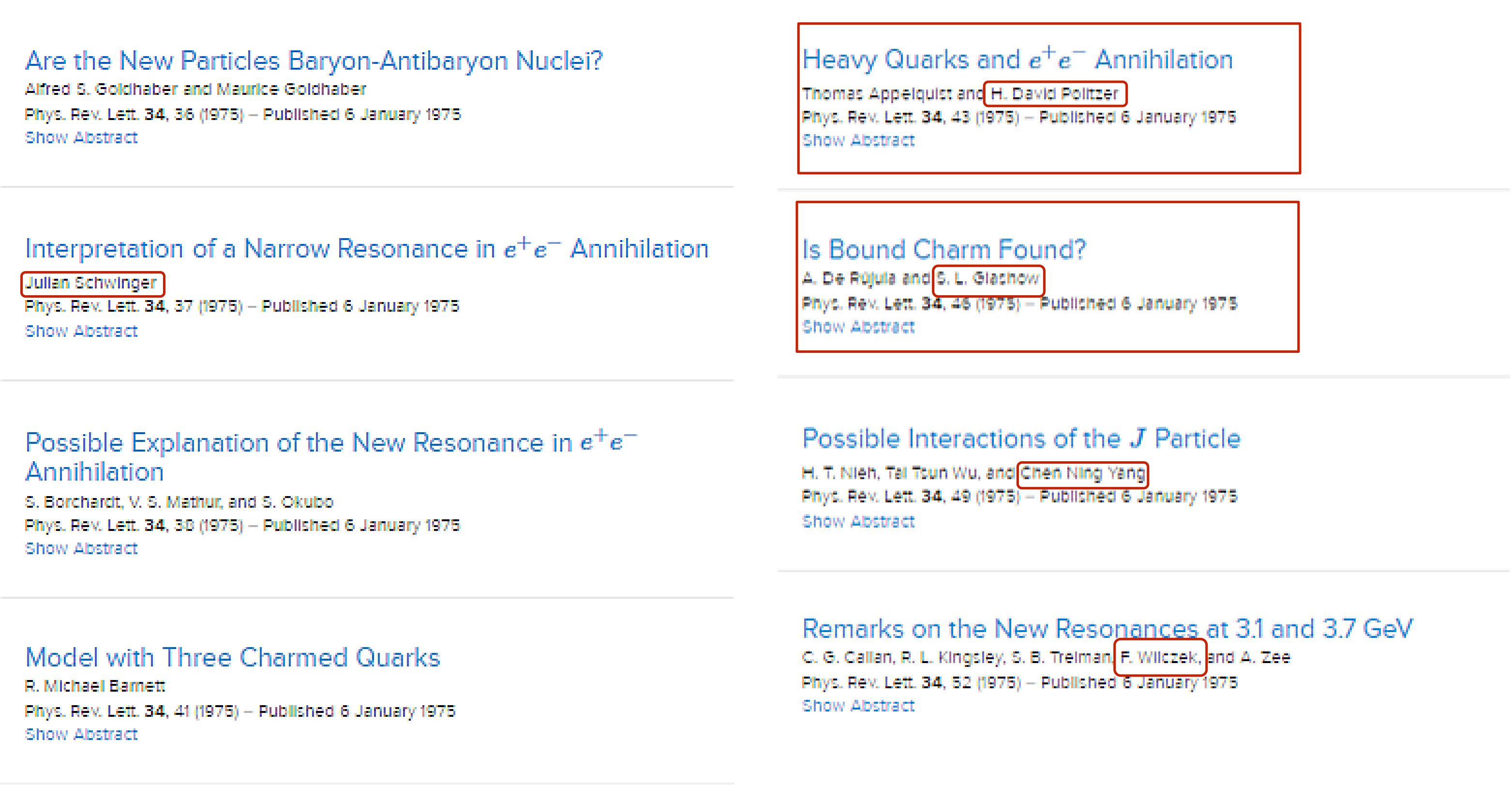

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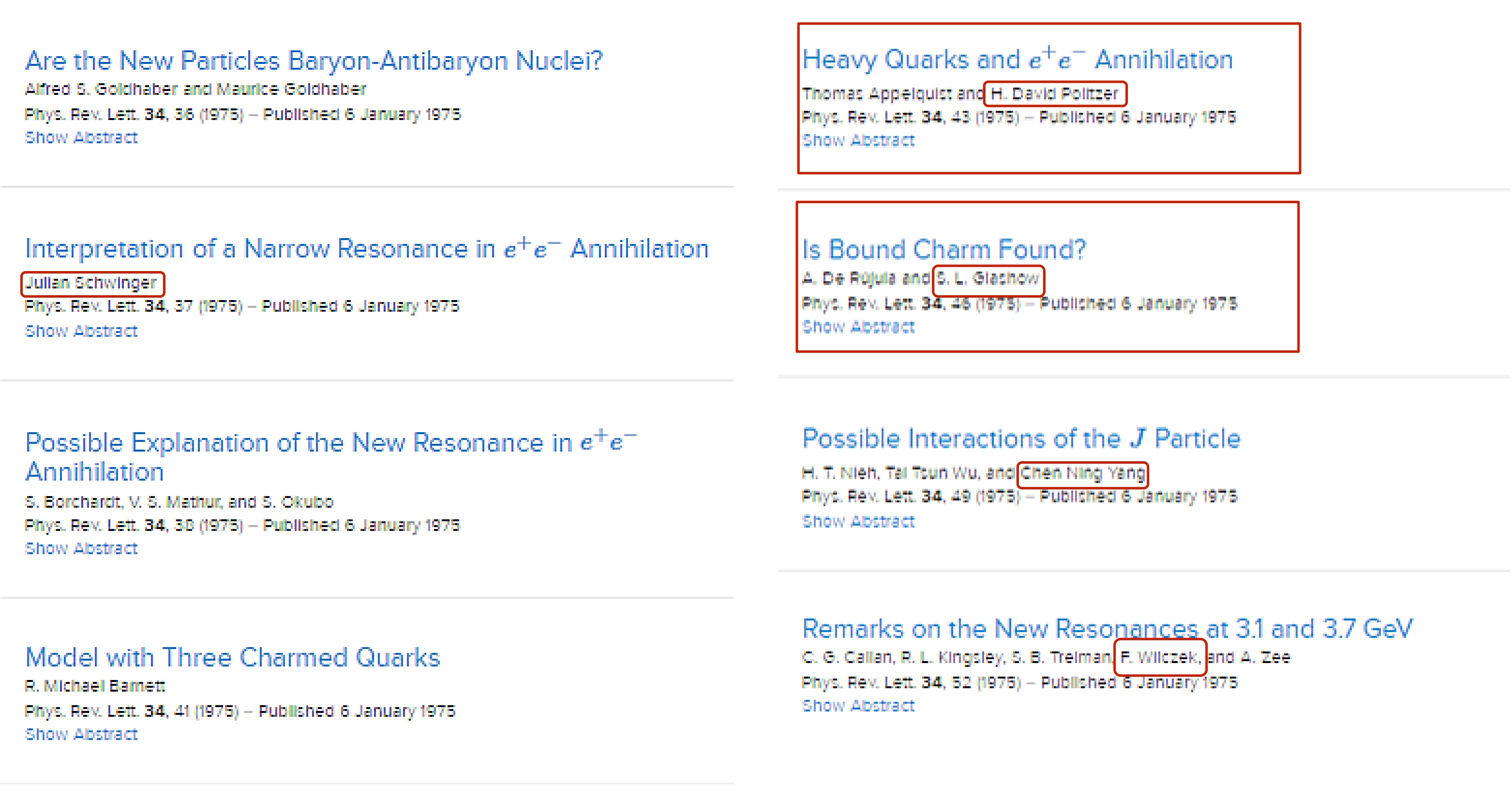

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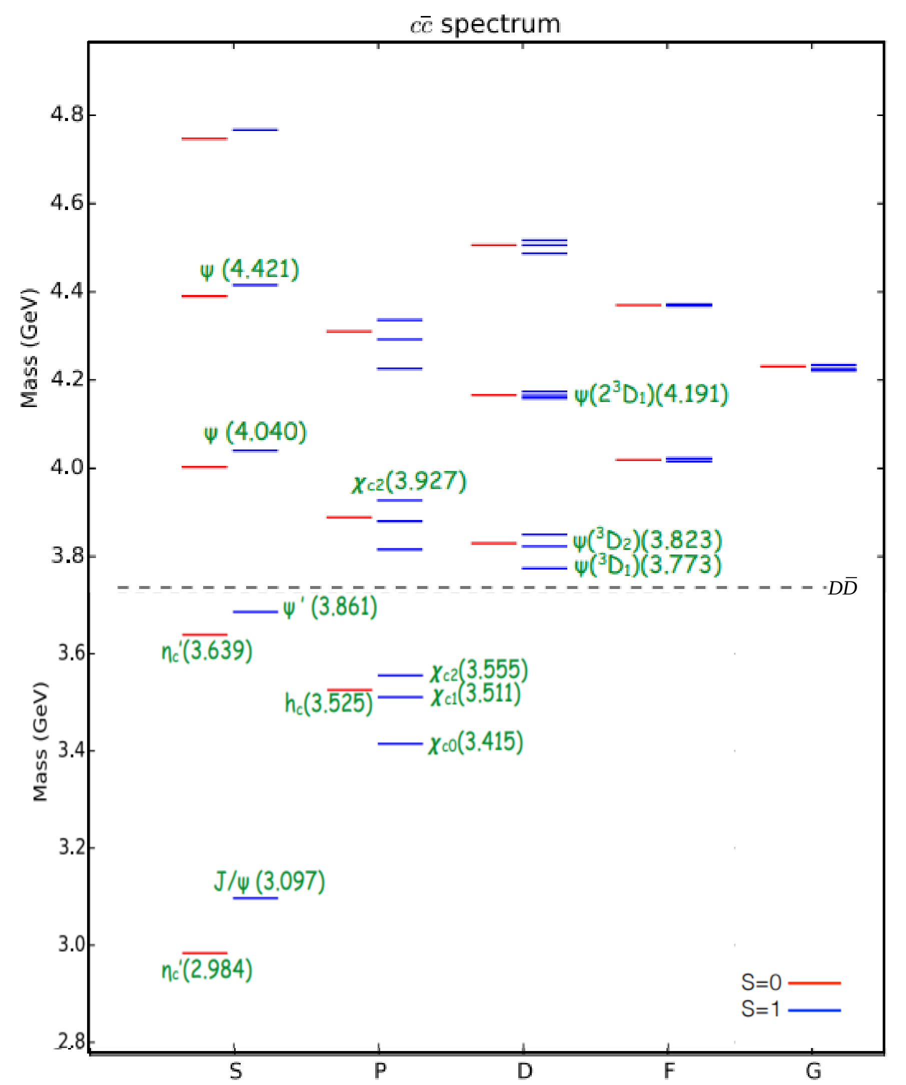
- The J/ψ is the lowest “orthocharmonium” ($1S$) bound state of two charmed quarks, produced just above threshold
- There should therefore be a whole spectrum of atom-like charmonium bound states. The second of these, the $\psi(2S)$ was soon found, and the entire spectroscopy remains an active area of study

Charmonium spectroscopy

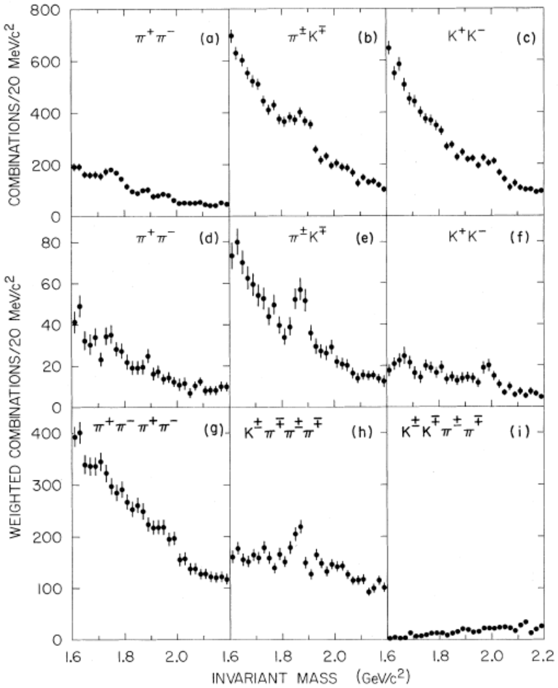


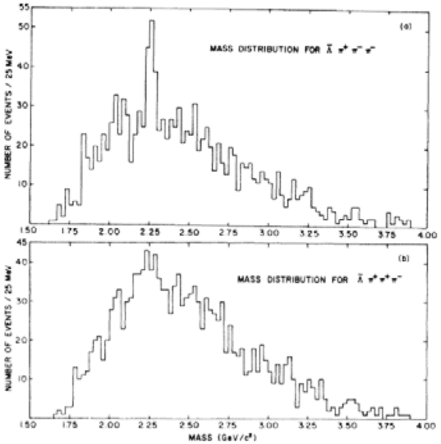
Derived from E. Eichten, FPCP 2016

S=0

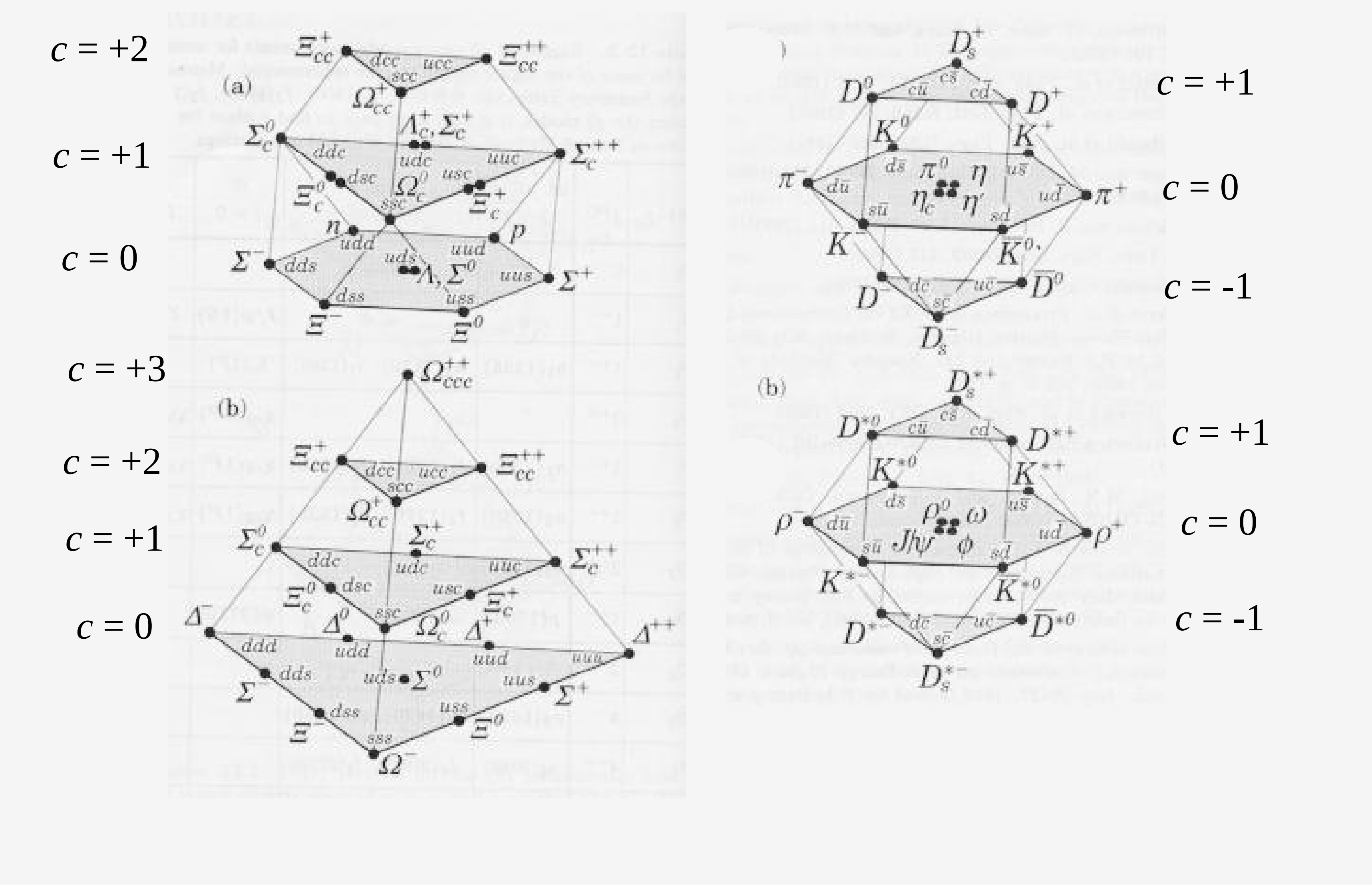
Charmed mesons and baryons

- The success of the GIM mechanism idea and the J/ψ discovery brought immediacy to the search for charmed quark-containing mesons and baryons
- The basic phenomenology, from charmonium spectroscopy to weak decays of charmed mesons and baryons was understood in detail (*c.f.* Gaillard, Lee and Rosner)
- The search for charmed hadrons became intense
  - Many experiments at Fermilab, for example, were quickly retooled to search for high p_t leptons as a signature of semileptonic decays of charm mesons
- The race was won at SPEAR by the same group that found the ψ, discovering the D^0 meson at 1865 MeV in the $K^{\pm}\pi^{\mp}$ and $K^{\pm}\pi^{\mp}\pi^{\pm}\pi^{\mp}$ final states
- The first charmed baryon the Λ_c^+ was found by E87 at Fermilab in photoproduction
- The D^+ and F^+ (D_s^+) soon followed, and the charm multiplets filled out



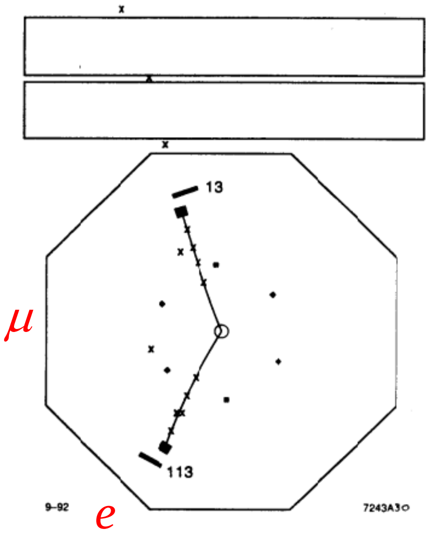


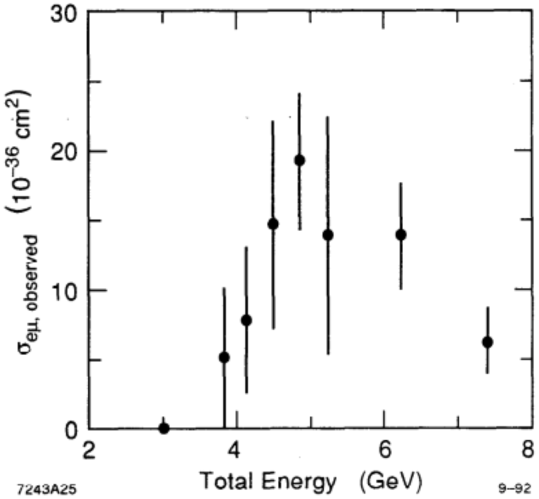
Four quarks: charmed mesons and baryons



The τ lepton discovery

- Were there charged leptons heavier than the electron and muon?
- Yes: the τ lepton, with a mass of 1.777 GeV, was also discovered in e^+e^- annihilation at SPEAR in 1975
  - The signature was a final state with an electron, a muon and missing energy, representing the process $e^+e^- \to \tau^+\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau, e^+\nu_e\bar{\nu}_\tau$
  - The production cross section exhibited the expected energy threshold and energy dependence

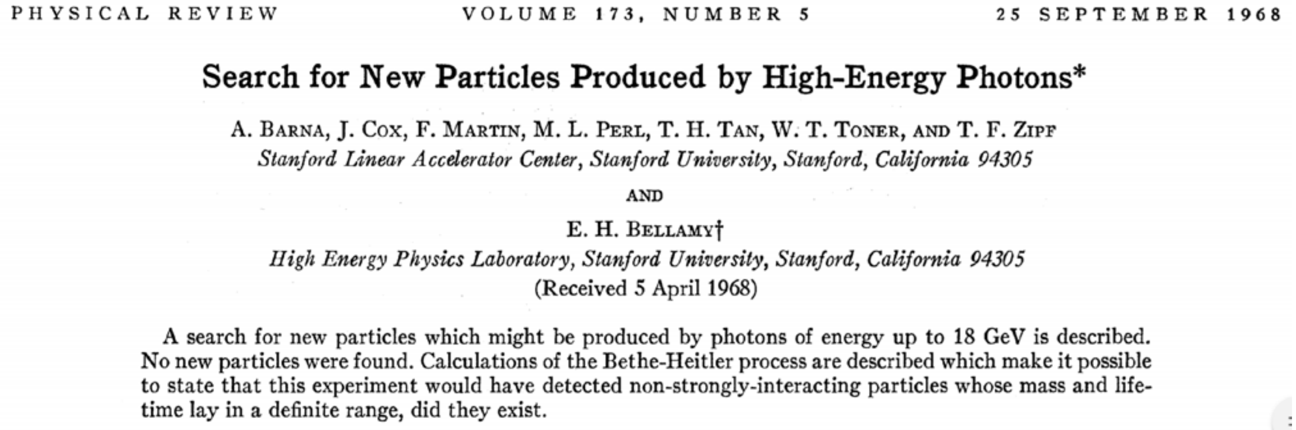




  - Later measurements called into question the consistency of the τ mass, leptonic branching fraction and lifetime, but these were resolved when the DELCO mass value was corrected by BES

The τ lepton search in context

- As noted by MIB, Perl's discovery of the τ was not serendipitous
- One of the first experiments he did at SLAC was a search for heavy leptons that set a limit up to ~1 GeV



PHYSICAL REVIEW VOLUME 173, NUMBER 5 25 SEPTEMBER 1968

Search for New Particles Produced by High-Energy Photons*

A. Barna, J. Cox, F. Martin, M. L. Perl, T. H. Tan, W. T. Toner, and T. F. Zipf
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

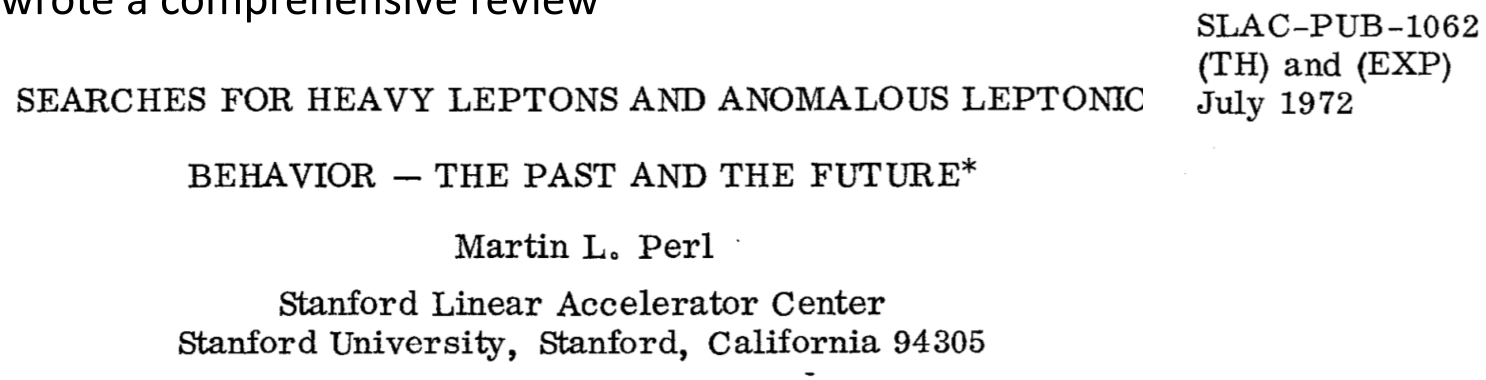
and

E. H. Bellamy†
High Energy Physics Laboratory, Stanford University, Stanford, California 94305

(Received 5 April 1968)

A search for new particles which might be produced by photons of energy up to 18 GeV is described. No new particles were found. Calculations of the Bethe-Heitler process are described which make it possible to state that this experiment would have detected non-strongly-interacting particles whose mass and lifetime lay in a definite range, did they exist.

- He then wrote a comprehensive review



SLAC-PUB-1062
(TH) and (EXP)
July 1972

SEARCHES FOR HEAVY LEPTONS AND ANOMALOUS LEPTONIC

BEHAVIOR — THE PAST AND THE FUTURE*

Martin L. Perl

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

- A heavy lepton search is specifically mentioned in SPEAR Proposal SP-2

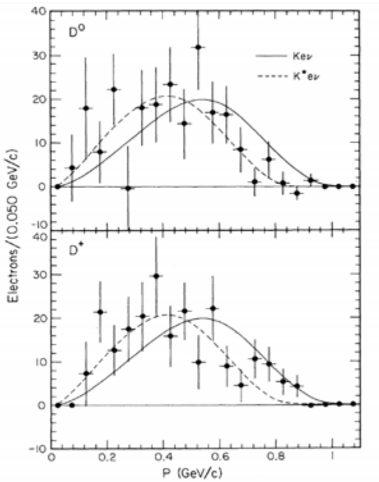
Charmed meson lifetimes

- In the naïve spectator model, the D^0 and D^+ lifetimes should be identical
- Soon after the discovery of charmed mesons, evidence began accumulating that the D^+ lifetime was substantially larger than that of the D^0
- There are two experimental approaches to the measurement:
  - The ratio of semileptonic branching fractions

$$\frac{B(D^+ \to e^+X)}{B(D^0 \to e^+X)} = \frac{\Gamma(D^+ \to e^+X)}{\Gamma(D^+ \to \text{all})} \cdot \frac{\Gamma(D^0 \to \text{all})}{\Gamma(D^0 \to e^+X)}$$

$$\simeq \frac{\Gamma(D^0 \to \text{all})}{\Gamma(D^+ \to \text{all})} = \frac{\tau(D^+)}{\tau(D^0)} = 2.3^{+0.5}_{-0.4}{}^{+0.1}_{-0.1}$$

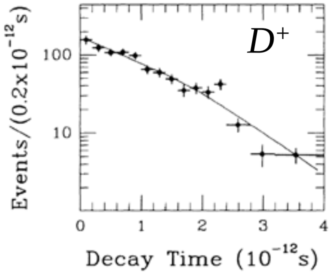
Mark III

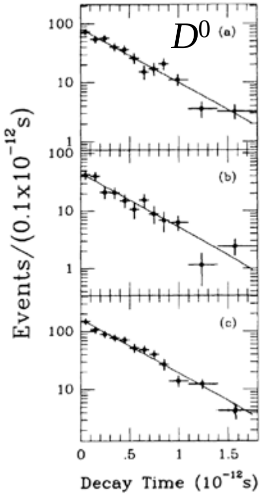


- Direct determination of the individual lifetimes

$$\frac{\tau(D^+)}{\tau(D^0)} = 2.1^{+0.04}_{-0.05}$$

E691

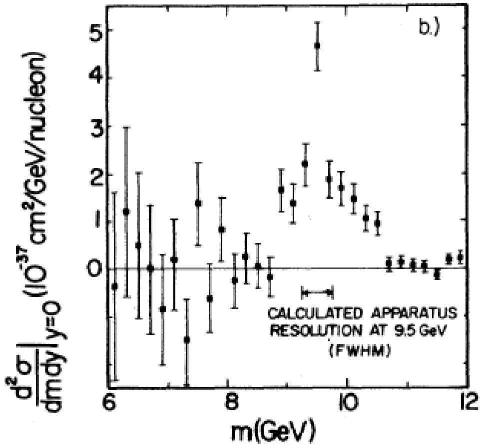


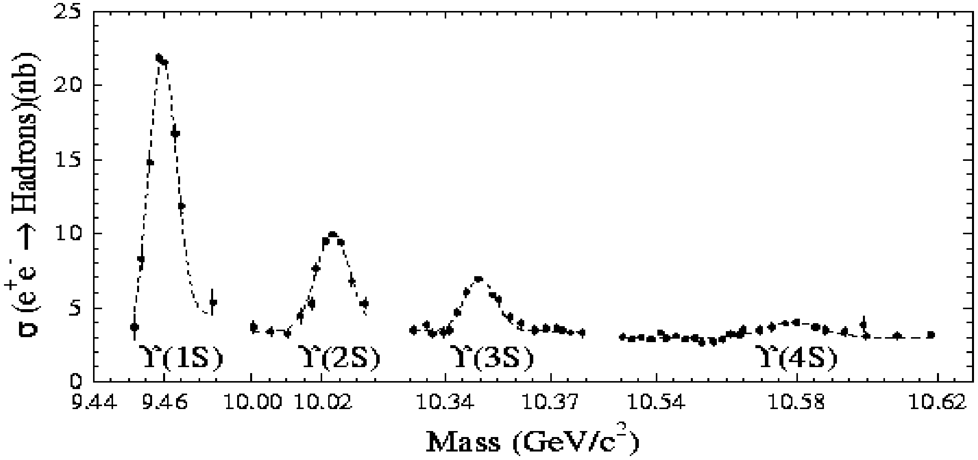


- It took some time for a robust theoretical understanding of this ratio (as well as the equality of D_s^+ and D^0 lifetimes) to develop
  - The explanation is the QCD enhancement of color-suppressed over color-enhanced terms in the weak Hamiltonian (Guberina, Nussinov Peccei, Rückl)
  - So what?

Bottom mesons

- Could there be more than four quarks?
  - A fifth quark, the much heavier b quark, was soon found by the Lederman group at Fermilab in 1977 in the $\mu^+\mu^-$ final state
  - There were actually three states seen: $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$
  - These are more clearly observed in e^+e^- annihilation: (CLE





- The $\Upsilon(4S)$ is of particular interest because it is above threshold to decay into pairs of b-quark containing mesons: $B^0\,(\bar{b}d)(\bar{B}^0\,(b\bar{d}))$ and $B^{\pm}\,(\bar{b}u, b\bar{u})$

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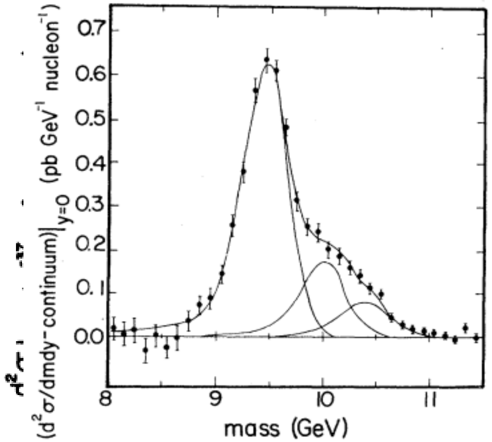

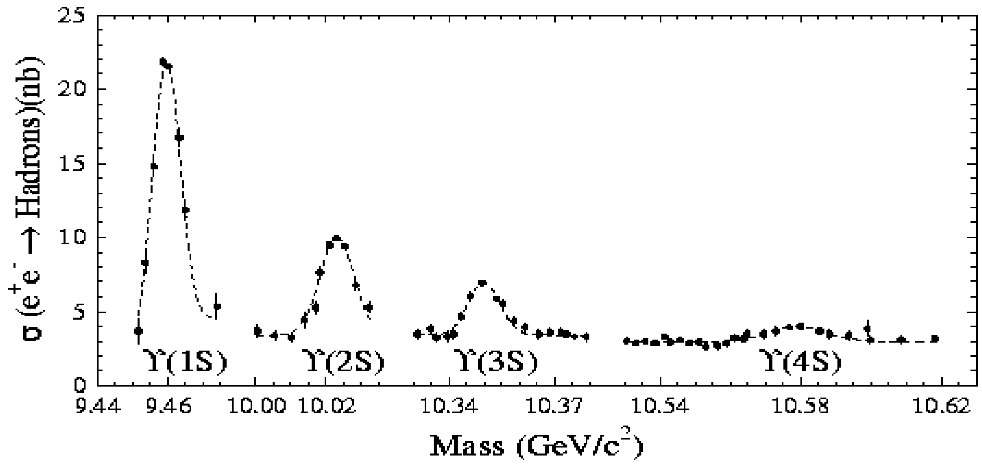

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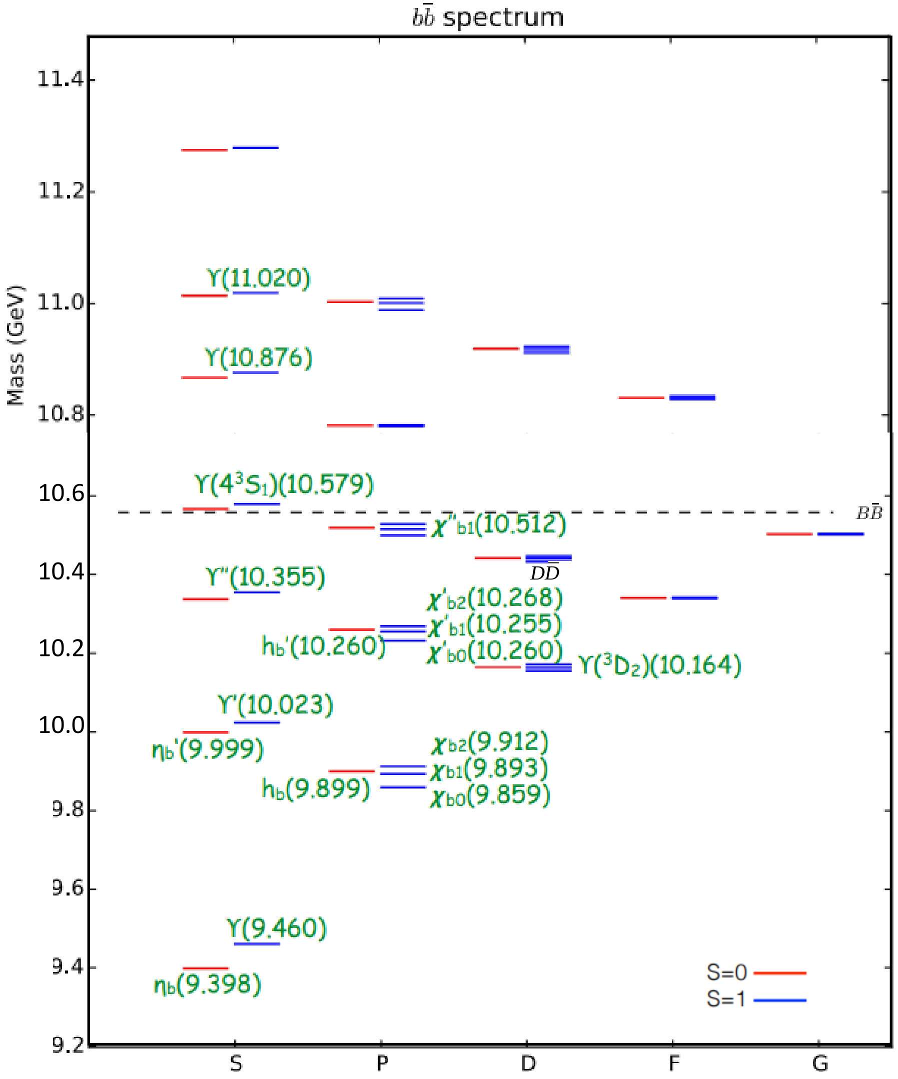

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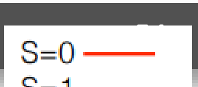


The CKM Matrix

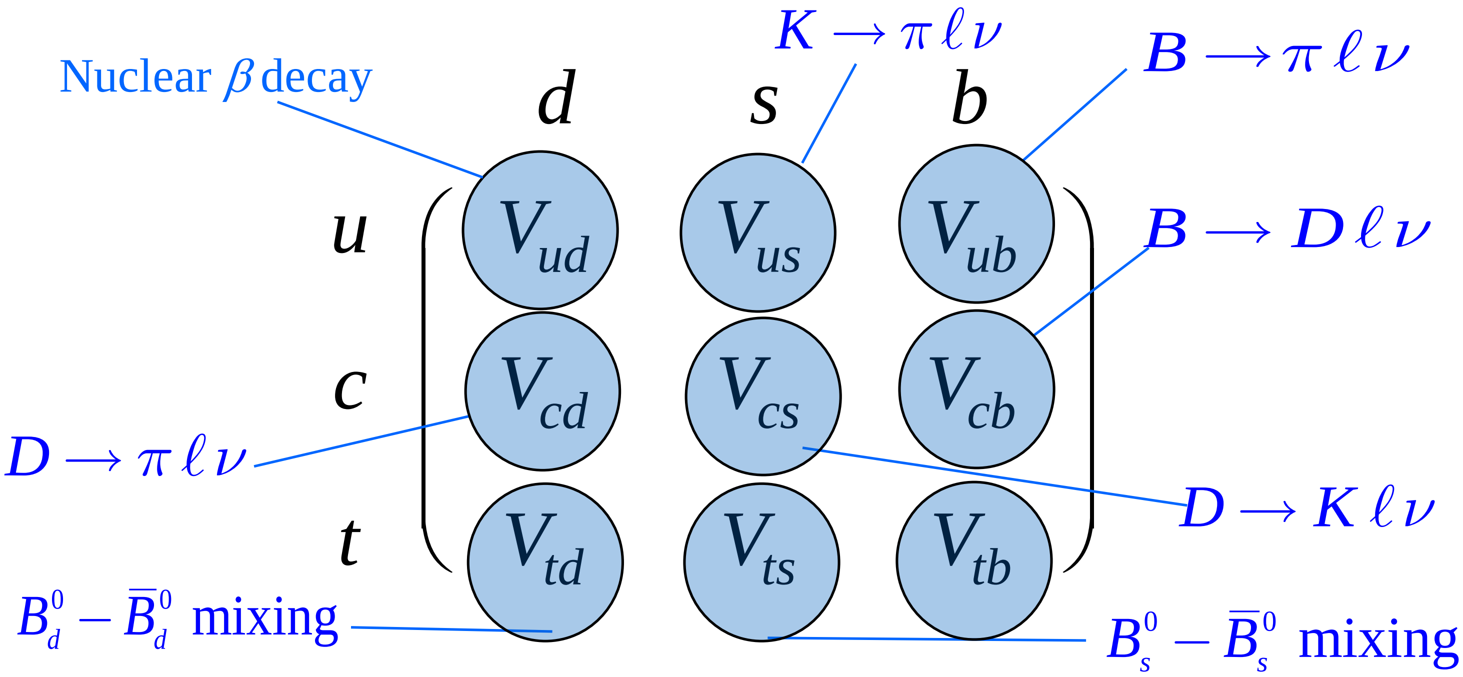
- When Cabibbo proposed his angle, and when quarks were conceived, some (Bj, Glashow, in 1964) speculated that there should be a fourth quark, based on the idea of quarks being in left-handed doublets
- Kobayashi and Maskawa in 1973 extended this idea to a three generation quark model (*i.e.,* three left-handed quark doublets)
- This was before the discovery of the b (1977) and t quarks (1996) and the τ
- Their motivation was the realization that in a six quark model, there is a **single weak phase** (plus three real numbers) that could account for the CP violation that had been observed in K_L meson decay
- As in the Cabibbo picture, the mass eigenstates of the quarks are not identical to the eigenstates of the weak Lagrangian
- The physical quarks are mixtures

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

- This became known as the Cabibbo-Kobayashi-Maskawa (CKM) matrix
- The three generation matrix is unitary

Measuring the CKM matrix elements

The CKM matrix elements are determined by a variety of measurements



$$\begin{array}{c|ccc} & d & s & b \\ \hline u & V_{ud} & V_{us} & V_{ub} \\ c & V_{cd} & V_{cs} & V_{cb} \\ t & V_{td} & V_{ts} & V_{tb} \end{array}$$

Nuclear β decay

$K \to \pi \ell \nu$

$B \to \pi \ell \nu$

$B \to D \ell \nu$

$D \to \pi \ell \nu$

$D \to K \ell \nu$

$B_d^0 - \overline{B}_d^0$ mixing

$B_s^0 - \overline{B}_s^0$ mixing

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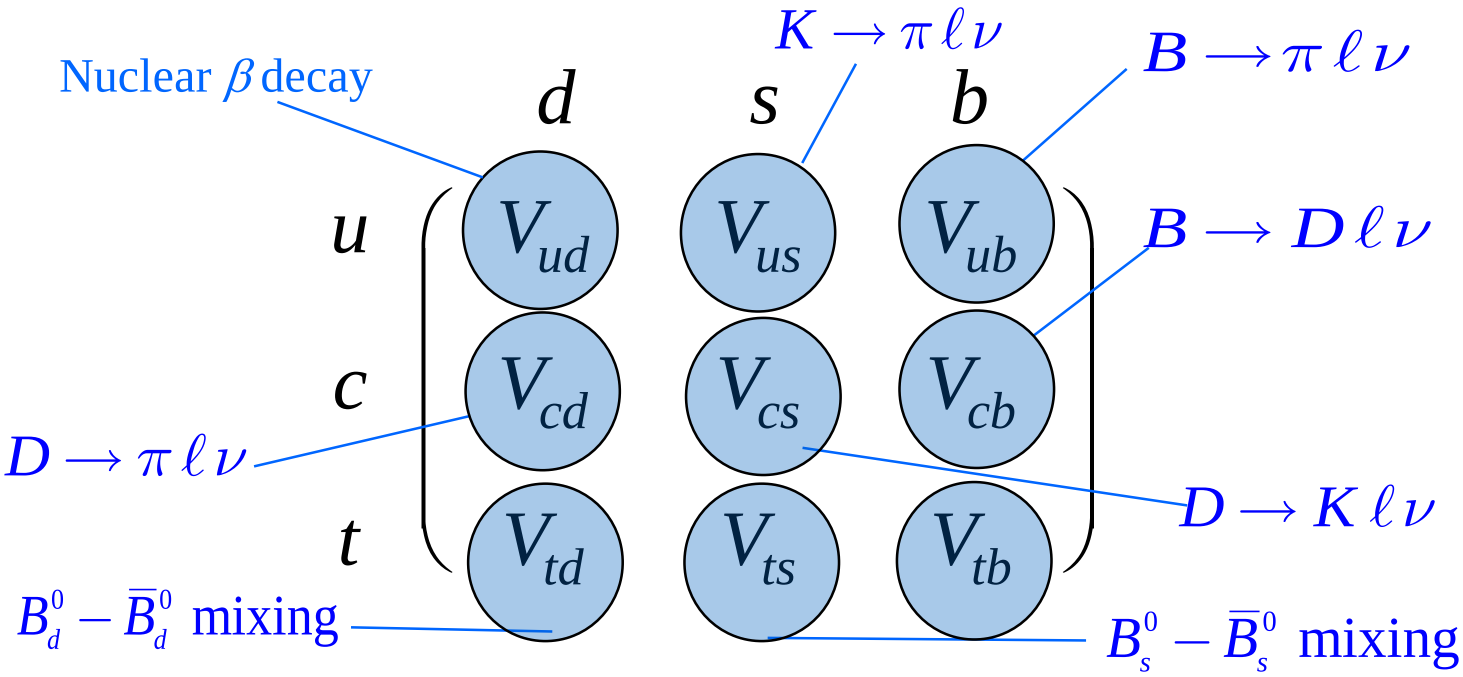

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The magnitudes of the CKM matrix elements are measured by determining the rates of various decay processes, primarily absolute branching ratios of inclusive and exclusive semileptonic decays, as well as the rates of neutral meson mixing.

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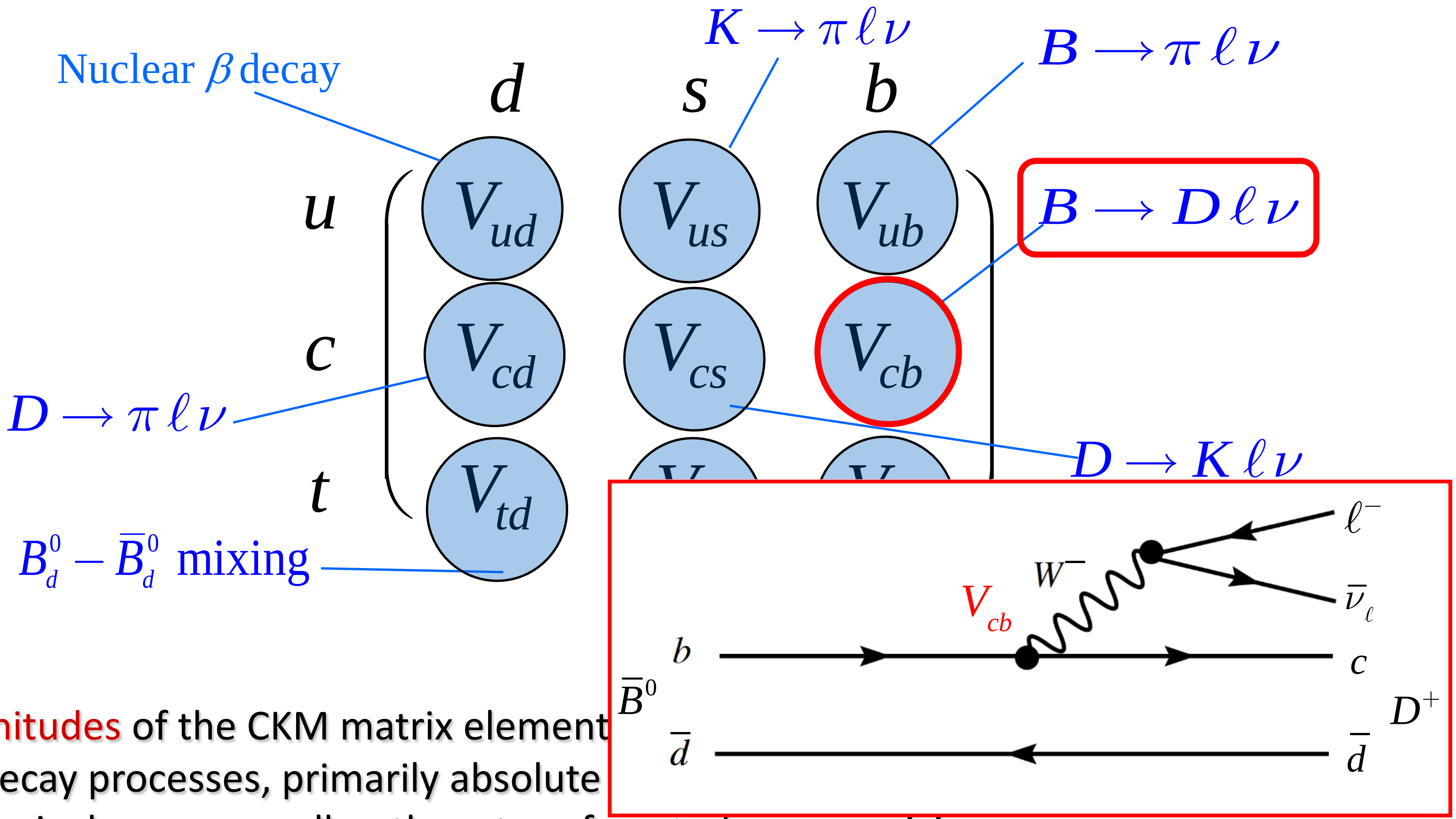

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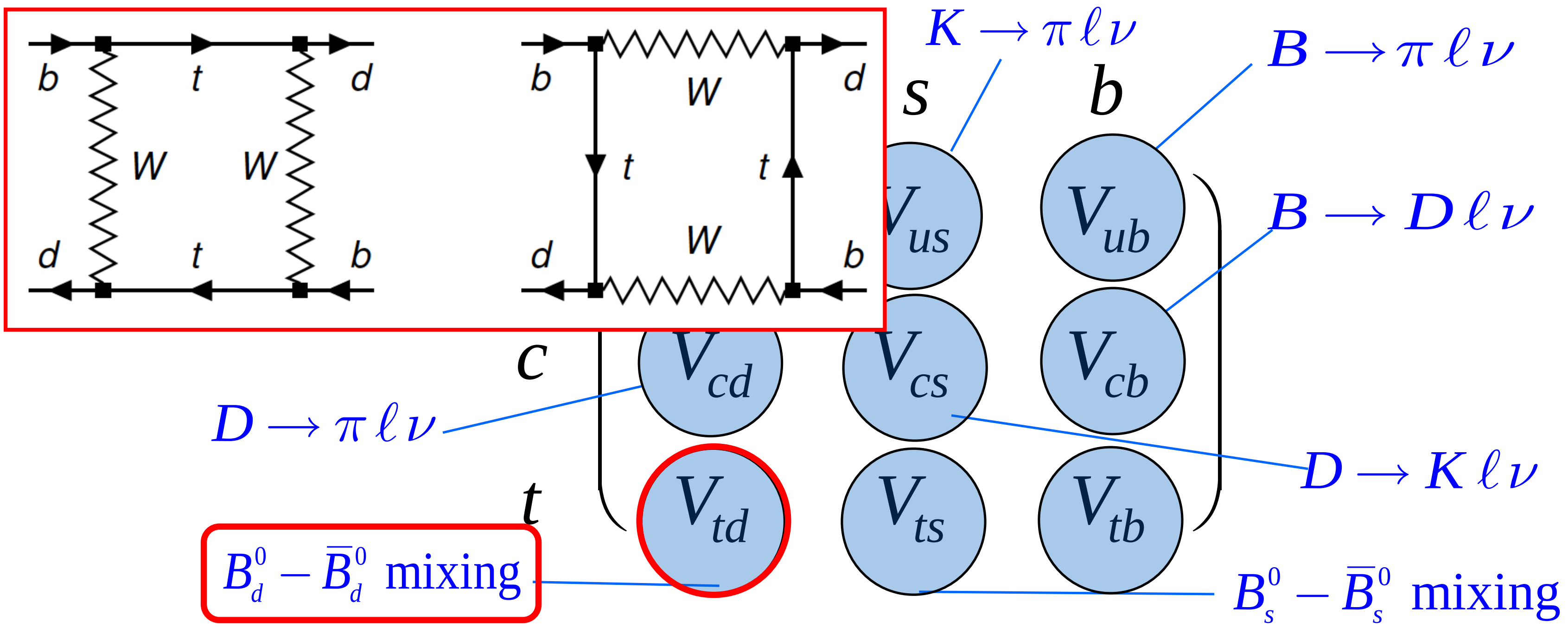


$K \to \pi \ell \nu$

$B \to \pi \ell \nu$

$B \to D \ell \nu$

$D \to \pi \ell \nu$

$D \to K \ell \nu$

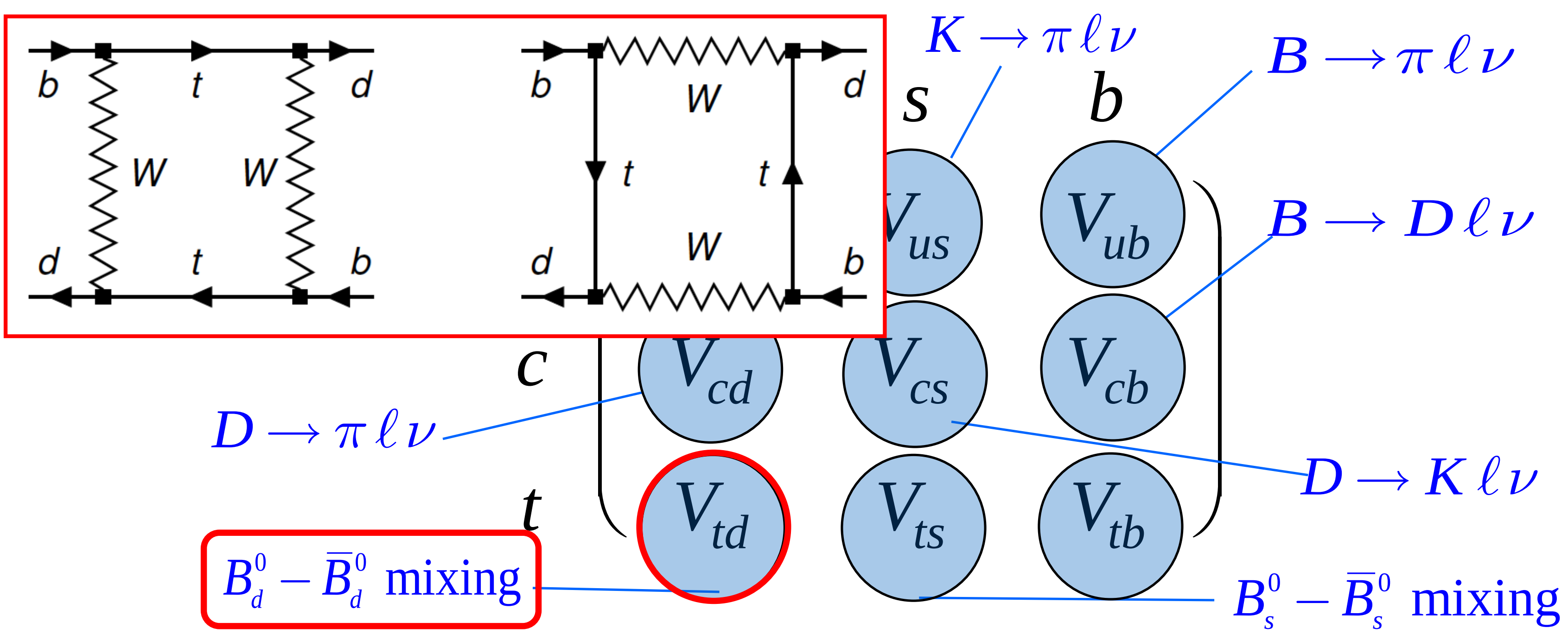
$B_d^0 - \bar{B}_d^0$ mixing

$B_s^0 - \bar{B}_s^0$ mixing

The magnitudes of the CKM matrix elements are measured by determining the rates of various decay processes, primarily absolute branching ratios of inclusive and exclusive semileptonic decays, as well as the rates of neutral meson mixing.

Measuring the CKM matrix elements

The CKM matrix elements are determined by a variety of measurements



$K \to \pi \ell \nu$

$B \to \pi \ell \nu$

$B \to D \ell \nu$

$D \to \pi \ell \nu$

$D \to K \ell \nu$

$B_d^0 - \bar{B}_d^0$ mixing

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The magnitudes of the CKM matrix elements are measured by determining the rates of various decay processes, primarily absolute branching ratios of inclusive and exclusive semileptonic decays, as well as the rates of neutral meson mixing.

What about the *CP*-violating phase?

The Wolfenstein parametrization

- The Wolfenstein parameterization of the unitary CKM matrix

$$\begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

λ is the Cabibbo angle
A governs the B lifetime

- The imaginary parameter η is responsible for *CP* violation
- How do we measure η ?
- Answer: measure a *CP*-violating asymmetry through the interference of mixing and decays amplitudes in the rare decay $B_d^0 \to J/\psi K_S^0$

A B^0 can oscillate into a $\overline{B}^0$ before the decay

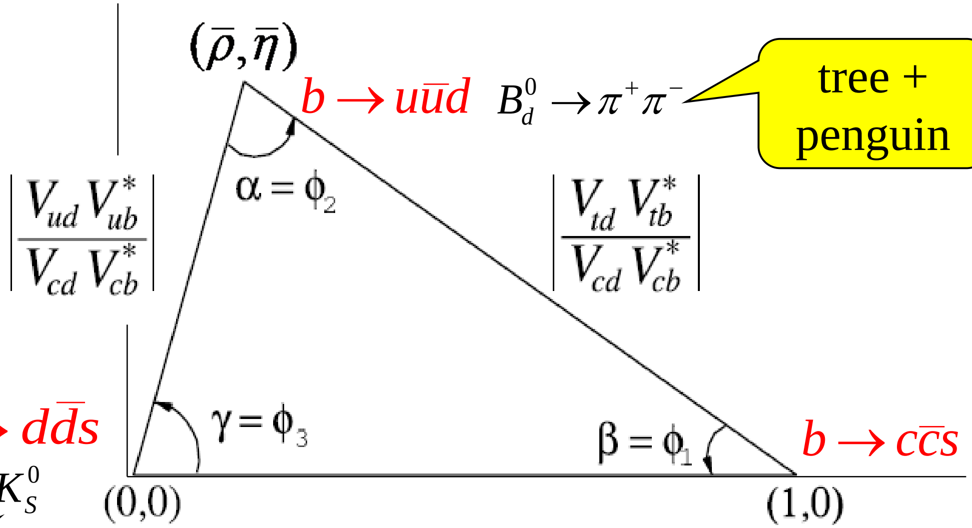
$$\begin{tikzcd} & B^0 \arrow[dr, "A"] & \\ \overline{B}^0 \arrow[ur, "q/p"'] \arrow[rr, "\overline{A}"'] & & J/\psi K_S \end{tikzcd} \qquad \begin{tikzcd} & \overline{B}^0 \arrow[dr, "\overline{A}"] & \\ B^0 \arrow[ur, "q/p"'] \arrow[rr, "A"'] & & J/\psi K_S \end{tikzcd}$$

Is $\Gamma\left(B^0_{phys}(t) \to f_{CP}\right) = \Gamma\left(\overline{B}^0_{phys}(t) \to f_{CP}\right)$?

If not, *CP* is violated in *B* meson decay

The Unitarity Triangle (Bj, Jarlskog)

- There are six triangular unitarity conditions: one triangle (the B triangle) has sides of comparable length $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$
- This can be plotted as a closed figure, for fixed λ and A, in the ρ,η plane



$B_d^0 \to \pi^+\pi^-$

tree + penguin

$b \to d\bar{d}s$

$B_s^0 \to \rho K_S^0$

tree

$B_d^0 \to J/\psi\, K_S^0$

tree

$$\bar{\rho} = \rho\left(1 - \frac{\lambda^2}{2} + \ldots\right)$$

$$\bar{\eta} = \eta\left(1 - \frac{\lambda^2}{2} + \ldots\right)$$

$$\alpha/\phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) \quad \beta/\phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \quad \gamma/\phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

- The area of the unitarity triangle is proportional to the amount of CP violation in the Standard Model: the "Jarlskog Invariant"

$$J = \mathrm{Im}(V_{ik}V_{jk}^*V_{jl}V_{il}^*) = A^2\lambda^6\eta$$

Caltech

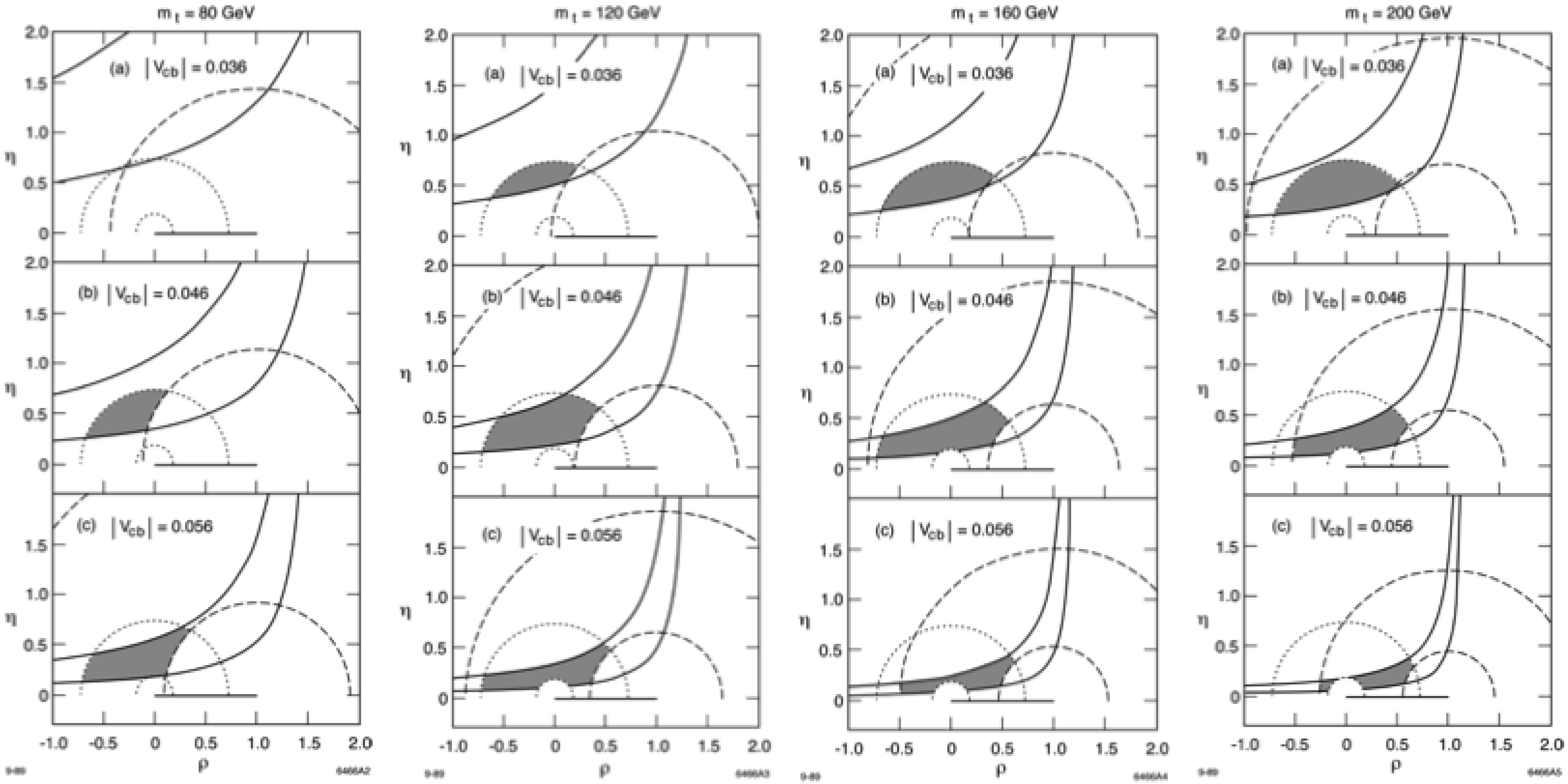
Motivations

- The possibility of measuring CP violation in B^0 decay was intriguing
  - Decays to CP eigenstates, $B^0 \to \psi K_S^0$ in particular, could be free of the hadronic engineering difficulties associated with interpretation of CP asymmetries in K decay and could be directly interpreted in terms of the CKM parameters
  - Measuring, in addition, various decay rates and mixing parameters allows unique overconstrained tests of the quark sector of the Standard Model
  - The Sakharov conditions for producing the matter-antimatter asymmetry of the universe require CP violation (the Wolfenstein parameter η)
    - There was no measurement of η, although CKM unitarity did not allow η to be large enough to do the job
    - Perhaps the measured value of CP violation would be larger than the SM value

The Unitarity triangle(s)

The unitarity triangle construction clearly illustrated the overconstrained Standard Model tests that would be made possible with a measurement of CP-violating quantities in the B meson system, but which triangle?

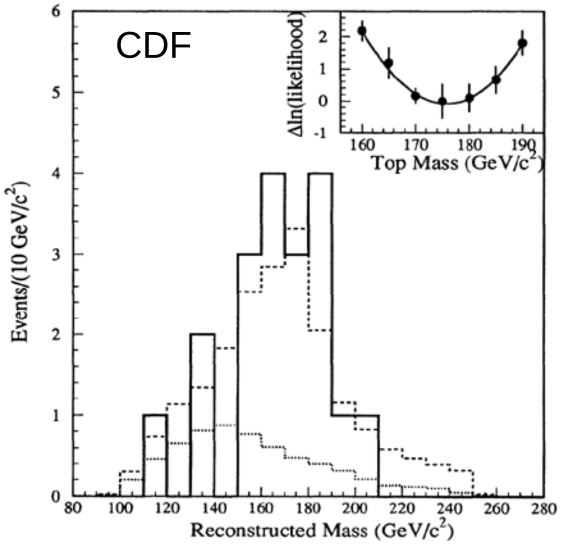
The top quark mass was not known. Not an academic question: dictates luminosity

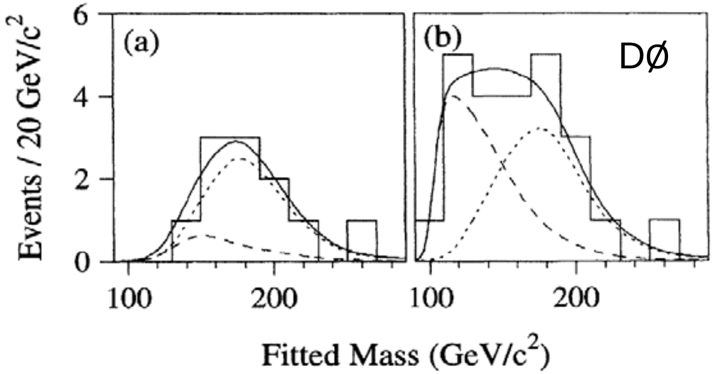


Dib, Dunietz, Gilman and Nir 1989

The top quark

- The search for the “last quark”, the top, took more than twenty years
- Without guidance as to the t mass, searches were conducted at the highest available cm energies, which steadily increased (PEP, PETRA, SPPS, TRISTAN, LEP, Tevatron)
- Since the mass is so high, the t quark decays in ~10^{-26} seconds at the actual mass, before forming hadrons, so the search technique differs from that of the c and b quarks
  - In a search involving associated production of a high p_t lepton with two hadron jets from the process $W \to t\bar{b}$, the UA1 experiment at CERN (540 GeV) claimed in 1984 a signal indicating a t quark mass of ~40 GeV
  - The actual discovery of the top quark was achieved in 1996 by the CDF and DØ collaborations at the Fermilab Tevatron (1.8 TeV) in the channel lepton + $\geq$4 jets





The top quark mass is now precisely measured by CDF, DØ, ATLAS and CMS

m_t =173.34 ± 0.27 (stat) ± 0.71 (syst) GeV

The Unitarity triangle(s)

The unitarity triangle construction clearly illustrated the overconstrained Standard Model tests that would be made possible with a measurement of *CP*-violating quantities in the *B* meson system, but which triangle?

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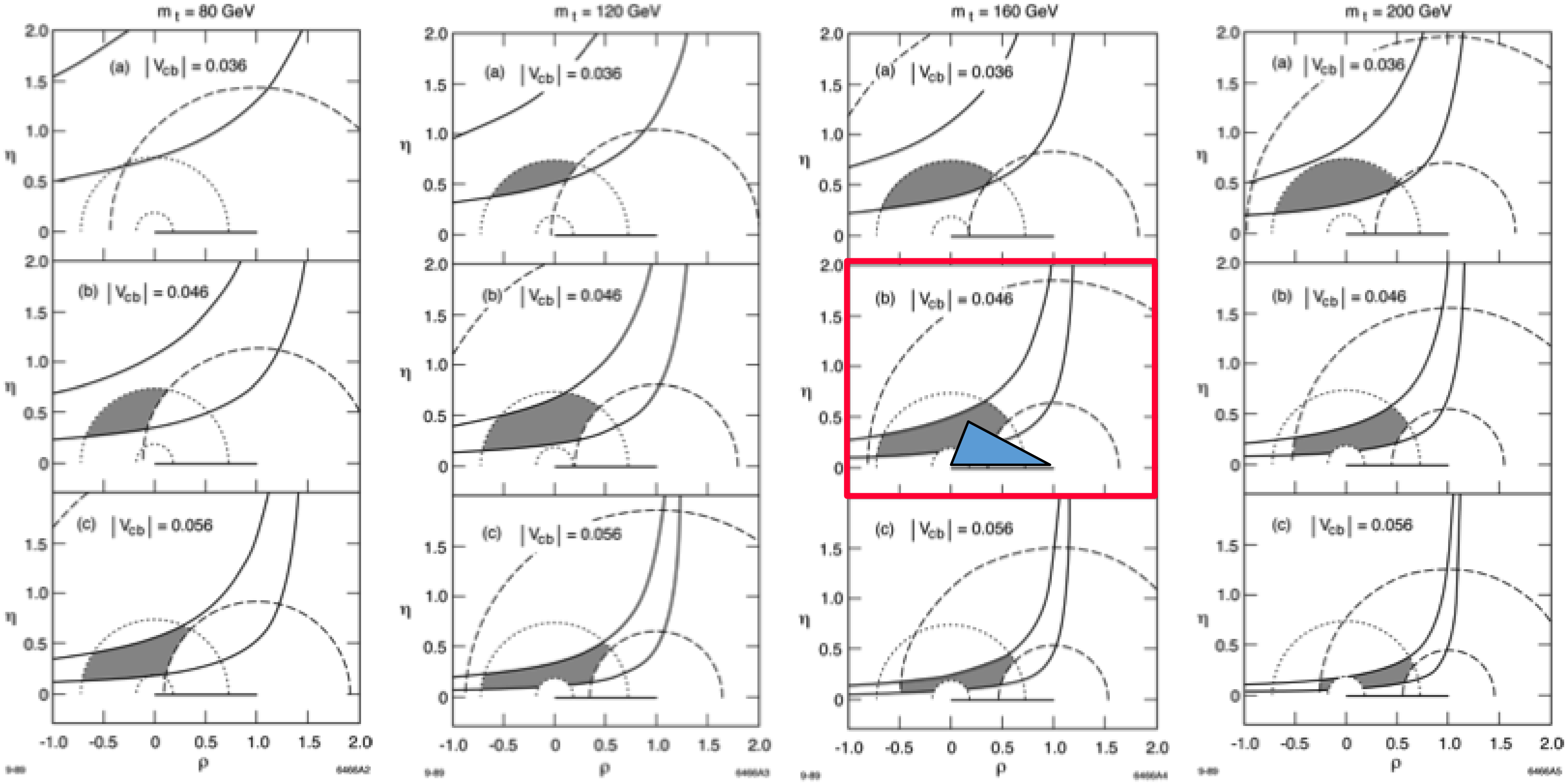


Dib, Dunietz, Gilman and Nir 1989

The recipe for measuring CPV in B^0 decay

- Recognize that CPV could manifest in the B^0 system $B \rightarrow D\pi$ (Carter, Sanda)
- Extend the idea to $B \rightarrow \psi K_s$ decays where D reconstruction is not needed (Bigi, Sanda)
- Recognize that the inclusive $B \rightarrow \psi X$ branching fraction could be large due to the enhancement of c_- over c_+ in the weak Hamiltonian (Fritzsch)

$$\Gamma(\mathrm{B} \rightarrow \psi(\mathrm{J}) + \mathrm{X})/\Gamma(\mathrm{B} \rightarrow \mathrm{all}) \approx 3\%$$

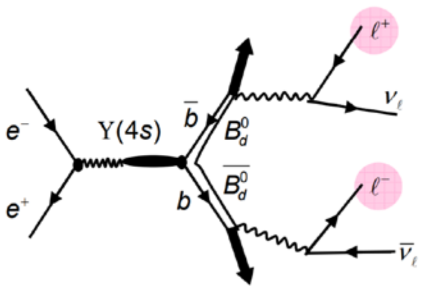
- Add one large B^0 meson lifetime
- Add a large pinch of $B^0\overline{B}^0$ mixing
- Produce >10^7 $B^0\overline{B}^0$ meson pairs at the $\Upsilon(4S)$ in e^+e^- annihilation
  - With the $\Upsilon(4S)$ in motion (Oddone) – need an asymmetric collider
- Build a 4π detector to reconstruct the B^0 decay vertices in time order and efficiently tag the B^0 meson flavor
- Find the resources to do all the above

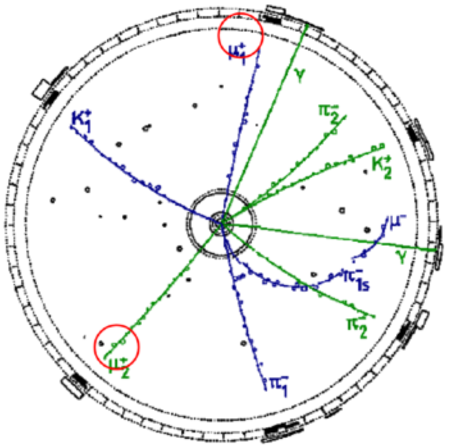
$B^0\overline{B}^0$ mixing

- In 1987 evidence for $B^0\overline{B}^0$ mixing was found by UA1 at CERN and ARGUS at DESY by measuring time-independent same sign dilepton events

ARGUS

$$\left.\begin{array}{l}\text{at } \sqrt{s}=10.58\text{ GeV}:\\ e^+e^-\to\Upsilon(4S)\to B^0\overline{B}^0\end{array}\right\}\ \sigma(B\overline{B})\approx 1\text{nb}$$





$B^0\to D^{*-}\mu^+\nu_\mu$
└ $\overline{D}^0\pi_s^-$
└ $K^+\pi^-$

$B^0\to D^{*-}\mu^+\nu_\mu$
└ $D^-\pi^0$
└ $\gamma\gamma$
└ $K^+\pi^-\pi^-$

$B^0\overline{B}^0\to\ell^+\ell^-$ unmixed

$$\left.\begin{array}{l}B^0B^0\to\ell^+\ell^+\\ \overline{B}^0\overline{B}^0\to\ell^-\ell^-\end{array}\right\}\ \text{mixed}$$

$$r=\frac{N(B^0\ell^+)+N(\overline{B^0}\ell^-)}{N(B^0\ell^-)+N(\overline{B^0}\ell^+)}=0.20\pm0.12$$

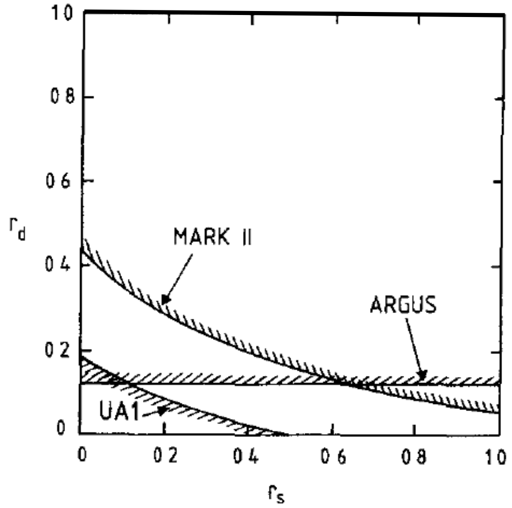
UA1

$$\chi_{d(s)}=\text{Prob}(B^0_{d(s)}\to\bar{B}^0_{d(s)})$$

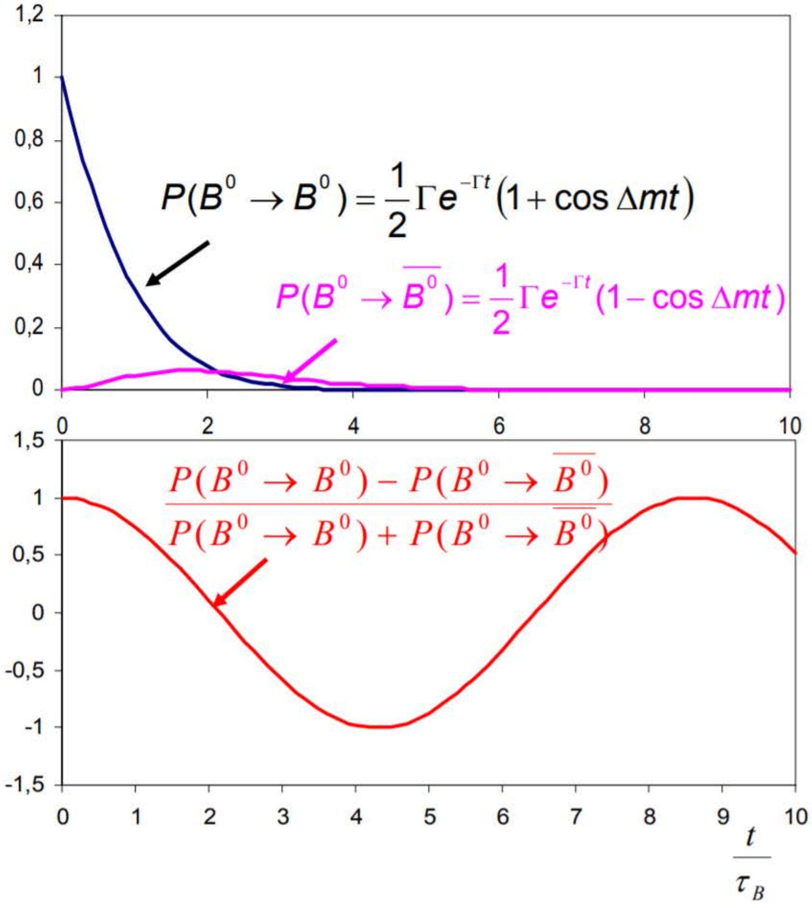
$$=\frac{BR(B^0_{d(s)}\to\mu^-+X)}{BR(B^0_{d(s)}\to\mu^\pm+X)}$$

They are related to χ by

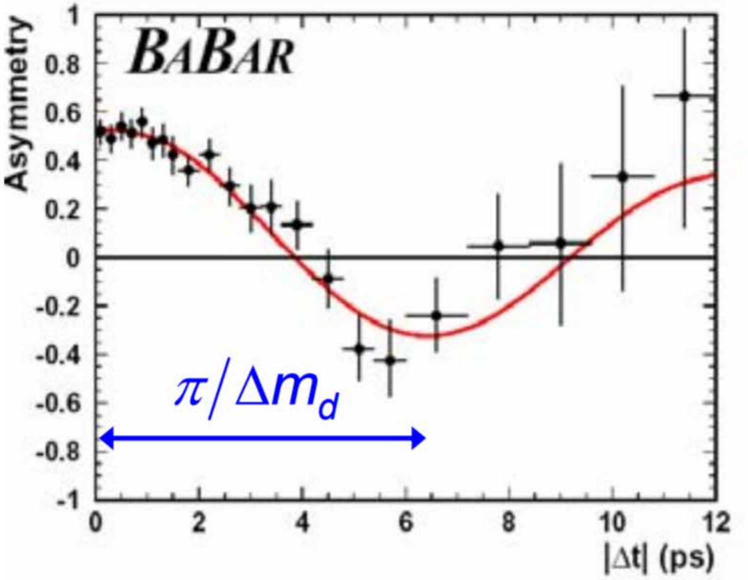
$$\chi=\frac{(BR)_d f_d\chi_d}{\langle BR\rangle}+\frac{(BR)_s f_s\chi_s}{\langle BR\rangle},$$



Modern time-dependent $B^0\overline{B}^0$ mixing



$$A = \frac{unmixed - mixed}{unmixed + mixed}$$



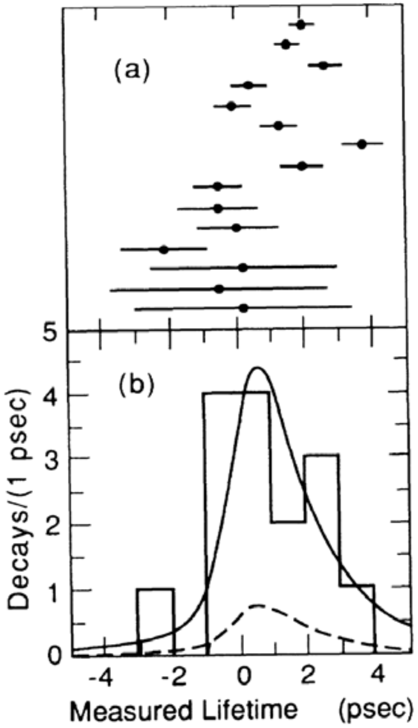
$$\Delta m_d = 0.506 \pm 0.006 \pm 0.004 \text{ ps}^{-1}$$

$$\approx \frac{0.774}{\tau_B}$$

The b hadron and B^0 lifetimes

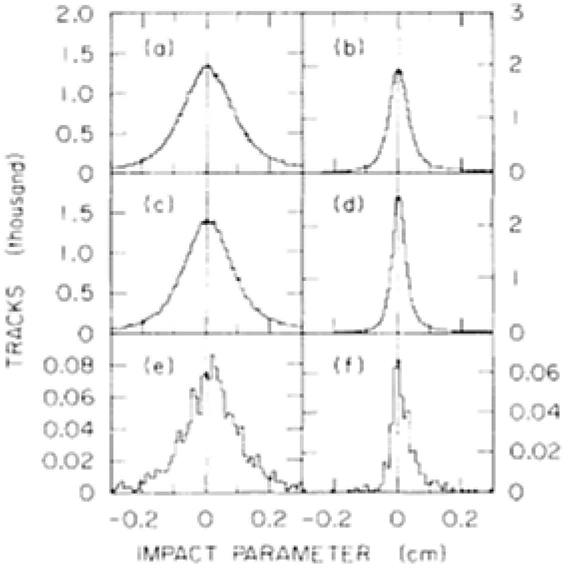
- The b hadron and B^0 lifetimes were measured at PEP, by Mark II and MAC to be surprisingly long

Mark II



$\tau_{B^0} = 1.20\,^{+0.52}_{-0.36}\,^{+0.16}_{-0.14}$ psec

MAC



$\tau_b = 1.29 \pm 0.20(\text{stat})$ ps

The Gold Rush

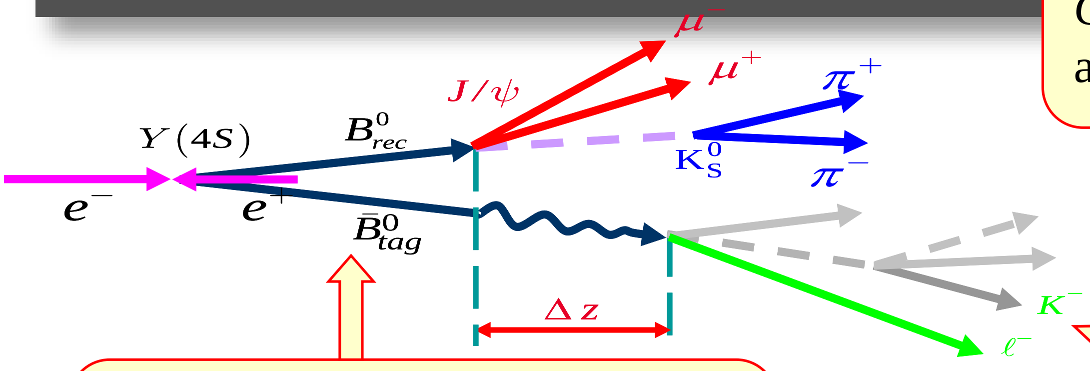
- There were at least 21 e^+e^- B Factory concepts and proposals (19 $\Upsilon(4S)$ + 2 Z^0) and several hadronic machine approaches (HERA-B, CDF…….)

$\Upsilon(4S)$ Storage Rings		$\Upsilon(4S)$ Linac-Ring Collider	$\Upsilon(4S)$ Recirculating Linear Collider	Z Factory $Z^0 \to b\bar{b}$
Symmetric	Asymmetric			
PSI (2)	APIARY	Grosse-Wiesmann	Amaldi/Coignet	SLC
BINP	CITAR	JLAB	ARES	LEP
KEK accumulator	PEP-II		UCLA	
CESR Plus	PETRA-II		TBA	
	ISR Tunnel			
	KEK accumulator			
	KEK-B			
	CESR-B			

- Oddone's concept of using an asymmetric e^+e^- collider to boost the distance between the two decay vertices to a measurable regime found its practical realization with two equal circumference rings, implemented in a multibunch machine stabilized by feedback
- Two asymmetric colliders of this type, PEP-II and KEKB, were ultimately built

Overview of the analysis

Reconstruct exclusive *B* decays to *CP* eigenstates and flavor eigenstates and tag the flavor of the other *B* decay



Select B_{tag} events using, primarily, leptons and *K*'s from *B* hadronic decays & determine *B* flavor

Select B_{CP} candidates $(B^0 \to J/\psi K^0_S$, *etc.*$)$ and B_{flav} candidates $\left(B^0 \to D^{*-}\pi^+, etc.\right)$

Measure the mistag fractions w_i and determine the dilutions $D_i = 1 - 2w_i$

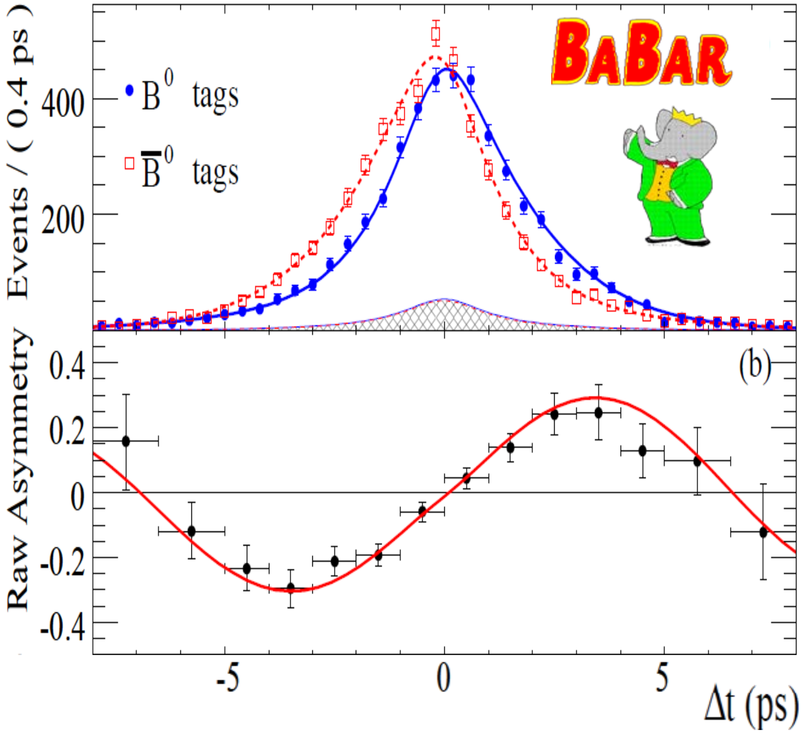
Δz ~ 250 mm at 9 on 3.1 GeV

Measure Δz between B_{CP} and B_{tag} to determine the signed time difference Δt between the decays

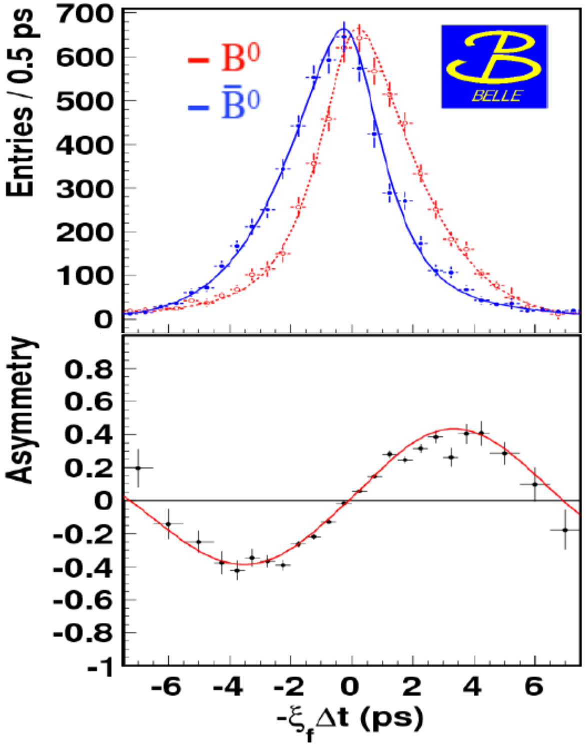
Determine the resolution function for Δz

$$R(\Delta t;\hat{a}) = \sum_{i=1}^{i=3} \frac{f_i}{\sigma_i\sqrt{2\pi}} \exp\left(-(\Delta t - \delta_i)^2\right)/2\sigma_i^2$$

CP asymmetry for tagged $J/\psi K_S$ decays

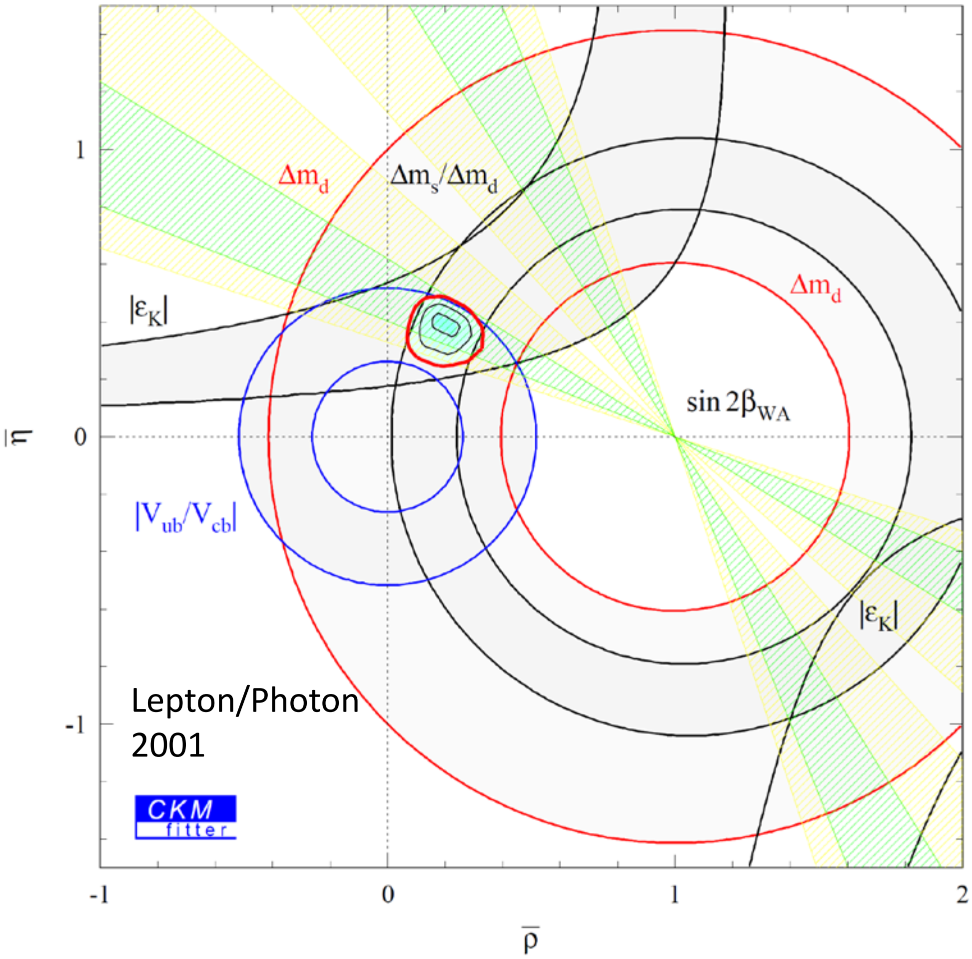


$\sin 2\beta$ = 0.657 ± 0.036 ± 0.012



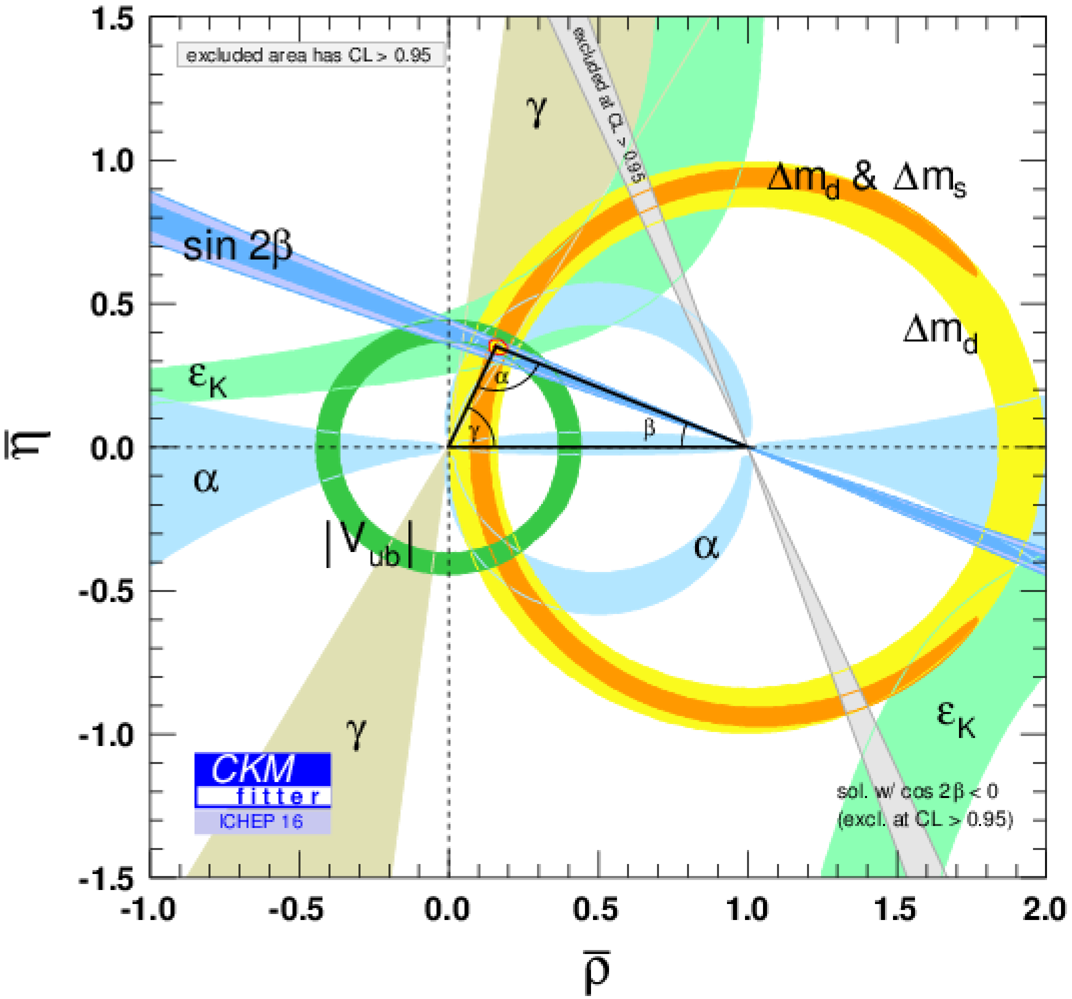
$\sin 2\phi_1$ = 0.670 ± 0.029 ± 0.013

Unitarity test - version 1



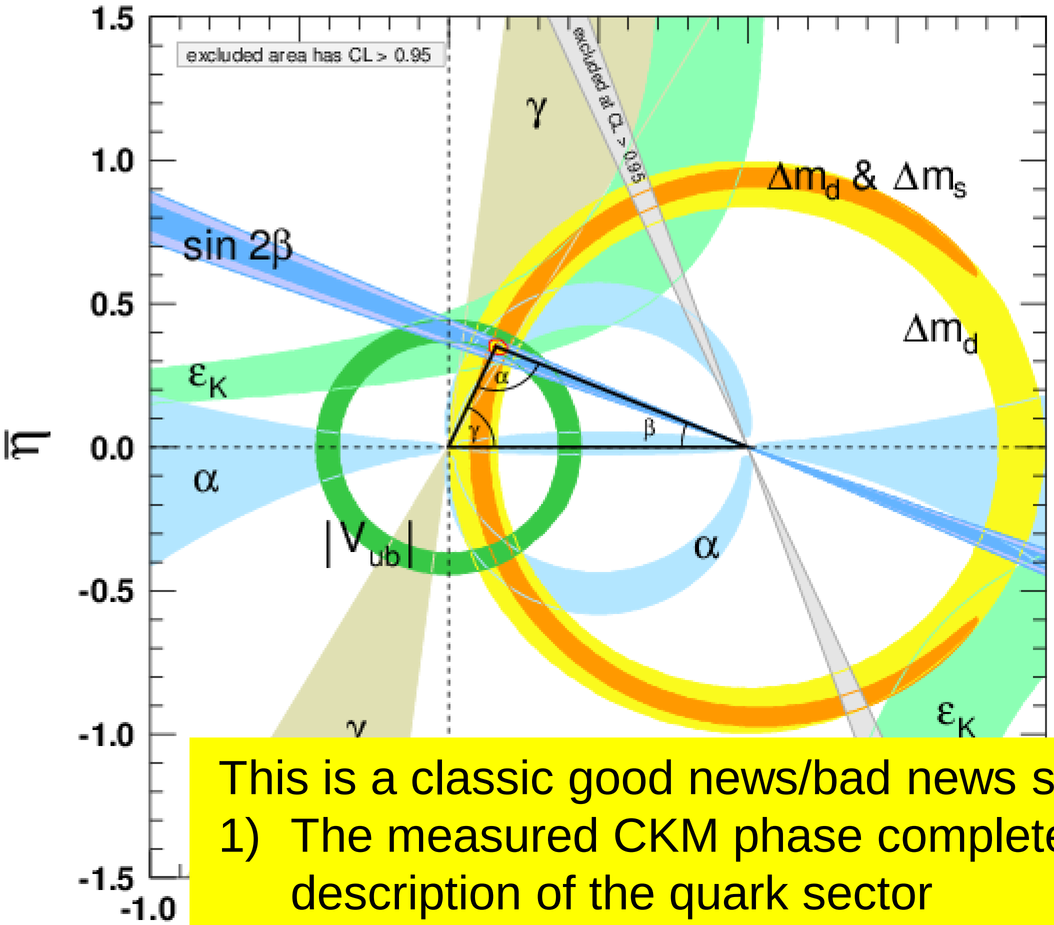
- *BaBar*, Belle measured $\sin 2\beta$
- The Standard Model passed the test

Unitarity triangle tests - current



- BABAR, Belle, CDF, LHCb, …. and K expts measured
- $\sin 2\beta$ (and resolved the trigonometric ambiguity)
- $\sin 2\alpha$
- γ
- Δm_d
- Δm_s
- V_{cb}
- V_{ub}
- Theory also improved
- And the Standard Model passed the test

Unitarity triangle tests - current



- *BABAR*, Belle, CDF, LHCb, …. and K expts measured

- $\sin 2\beta$ (and resolved the trigonometric ambiguity)
- $\sin 2\alpha$
- γ
- Δm_d
- Δm_s
- V_{cb}
- V_{ub}

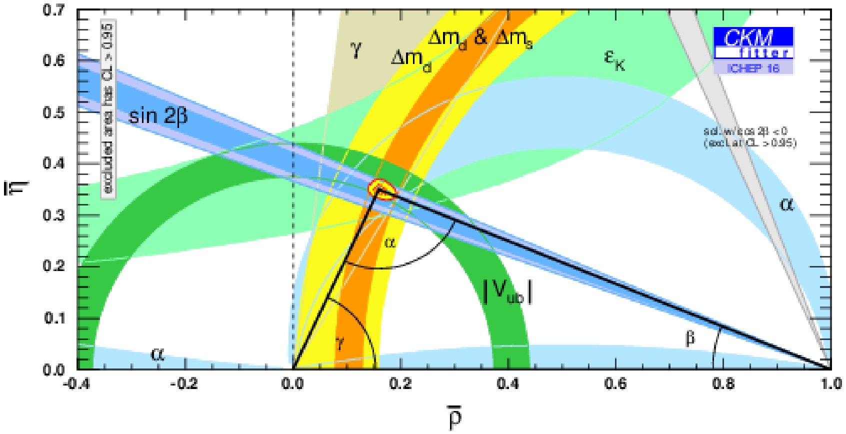
- Theory also improved

odel

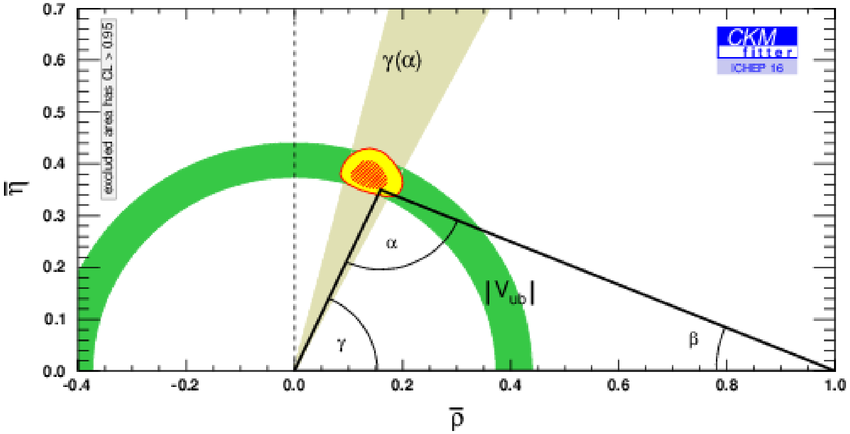
This is a classic good news/bad news situation:

1) The measured CKM phase completes the Standard Model description of the quark sector
2) We still have no understanding of the matter/antimatter asymmetry of the universe

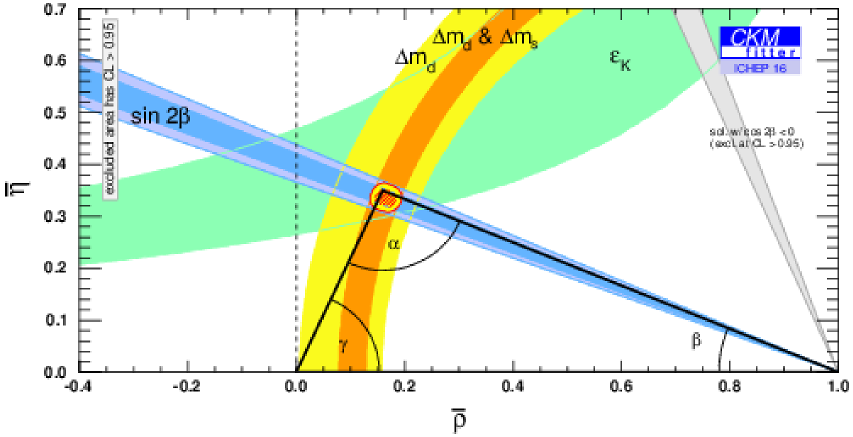
Further unitarity triangle tests



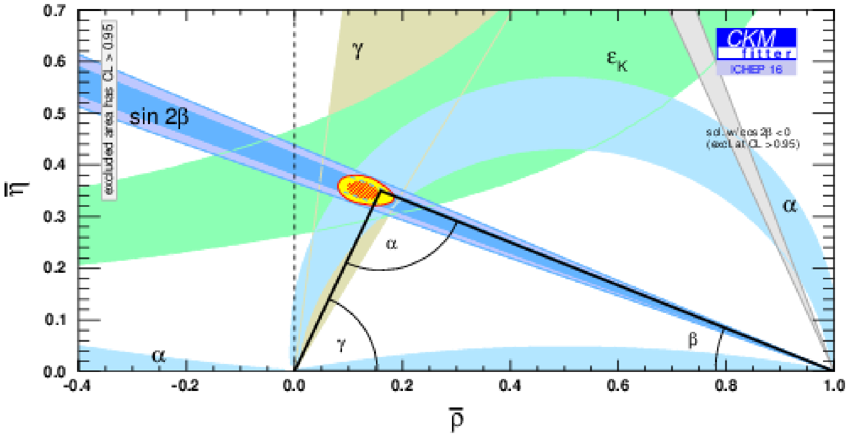
All measurements



Tree-dominated measurements



Loop (mixing)-dominated measurements



CP-violating measurements

Conclusion and outlook

- The Standard Model of the quark sector is experimentally verified to high precision
  - The road to this point, as I have discussed, has not been quite a straight one, embodying a complex interplay of theory and experiment
- Experimental focus is now therefore on searching for new states at high energy machines and for Standard Model prediction failures that could indicate new physics in loops
  - There are small experimental anomalies which may or may not be indications of new flavor physics
    - g-2
    - Indications of lepton universality violation in semileptonic B decays and $B \rightarrow D^{(*)} \tau \nu$
- The flavor oscillations of the neutral lepton sector provide *prima facie* evidence of neutral lepton flavor violation and therefore of physics beyond the SM (see Kearns talk)
- Searches for loop effects such as CPV in penguin decays and charged lepton flavor violation in τ decay and μ decay and μe conversion are an active area of investigation, with major sensitivity improvements in the next decade

Charged lepton flavor violation searches