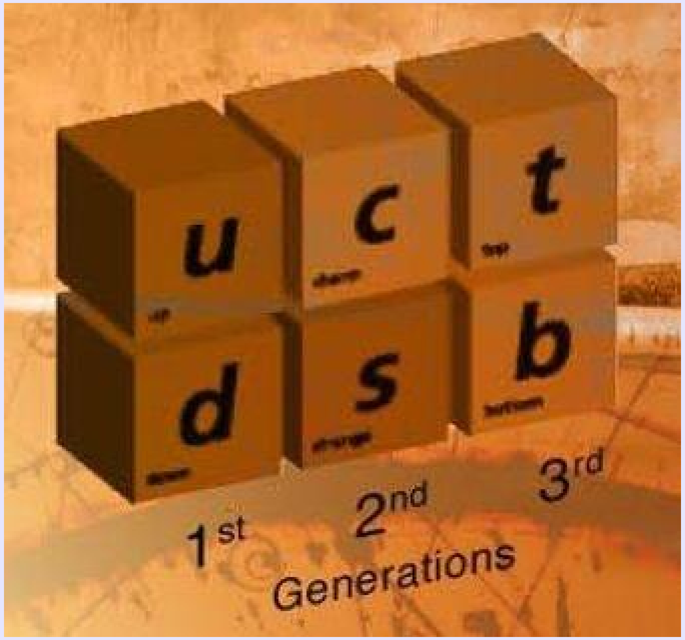
THE DISCOVERY OF THE TOP QUARK

Lina Galtieri (LBNL)

- Historical review of particle discoveries.
- Cosmic Rays gave the first information about particles beyond the electron and the proton.
- 1955:the first accelerators were developed by Lawrence, here at Berkeley(pbar discovered)
- 1960:the Hydrogen Bubble Chamber developed by L. Alvarez at LBL, allowed finding many particles.
- 1964: Gell-Mann and Zweig developed the quark model SU(3) Symmetry) to explain the existence of these particles.
- 1967-70 Glashow, Weinberg and Salam proposed the Standard Model
- 1973 Neutral Currents were found.

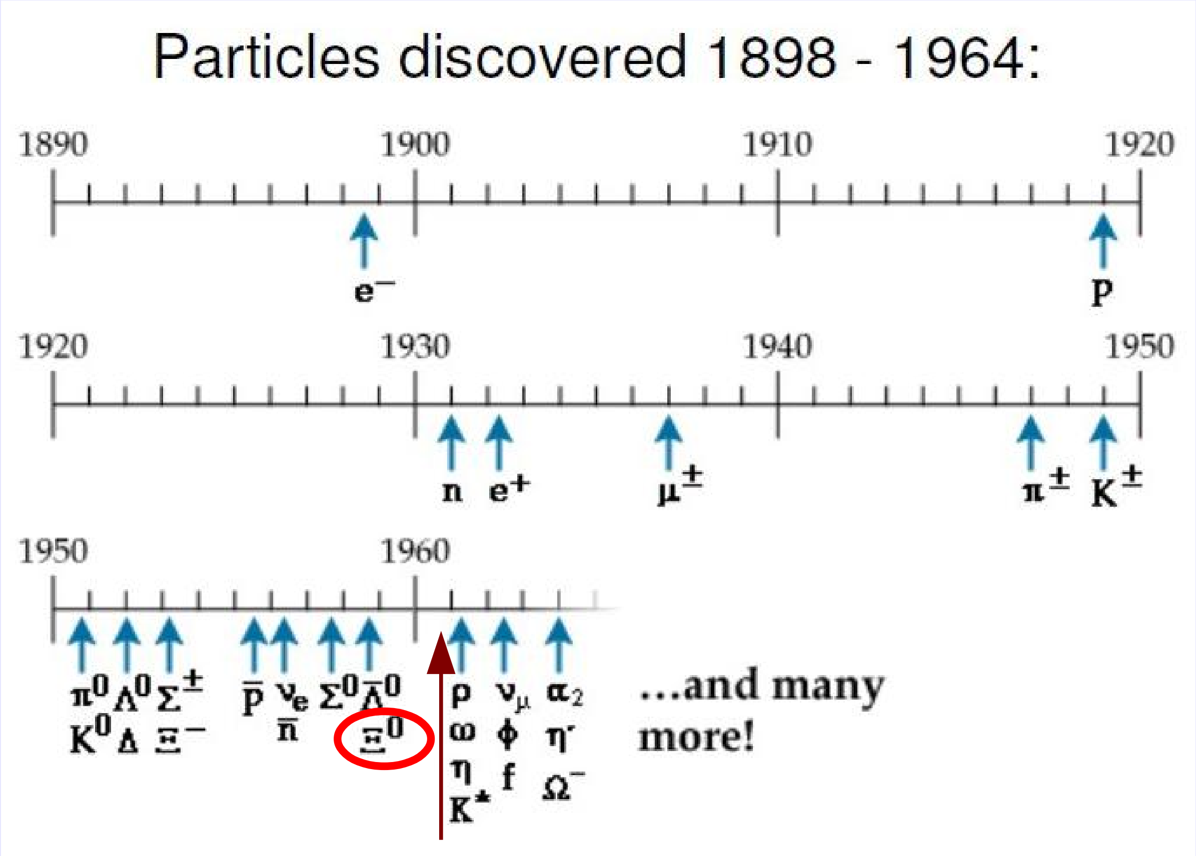
- 1974: The J/psi, bound state of c-c quarks is found
- 1975: the tau lepton was observed, confirmed in 1977
- 1977: the bottom quark is found
- 1995 : the top quark is found



The building blocks of matter today.
u, d, s and t are the ones LBL contributed the most.

THE PARTICLE EXPLOSION (1964)

Before 1960 most particles were discovered with cloud chambers or nuclear emulsions. By 1959 a new detector (Alvarez' hydrogen bubble chamber) was built at LBL. The first particle discovered was the Ξ^0

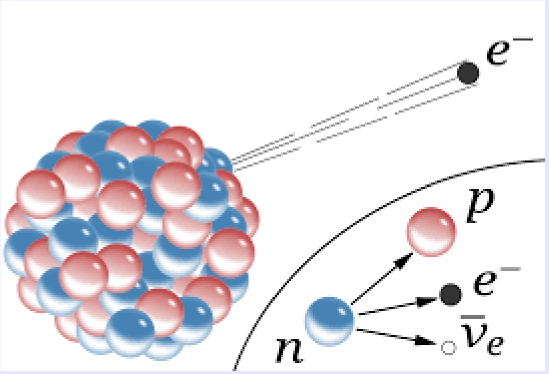


After the Ξ^0 18 more particles were discovered or co-discovered in the Alvarez' hydrogen bubble chambers

The Ξ^0 is a "stable" (lifetime ~10^{-10}sec) particle, while the other 18 are resonances i.e. they decay in a very short time

The neutron

The neutron decay into a proton was the beginning of particle physics. It is called a fermion because Enrico Fermi was the first to observe this decay.



The Bevatron and the antiproton

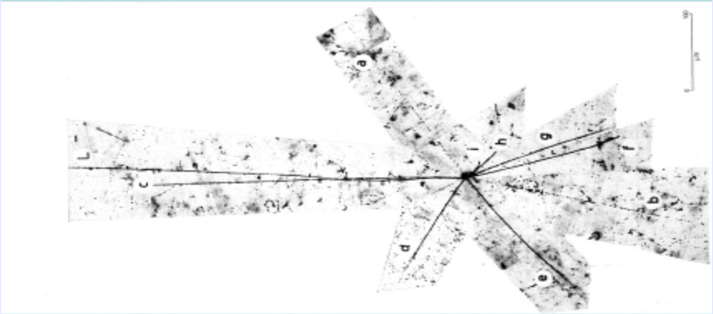
Lawrence invented the accelerators. The Bevatron accelerated protons up to 6.2 GeV into a copper target. One of the experiments proposed there, was a p-p collision study by the Segré group. They found the antiproton in 1955, for which they were awarded the 1959 Novel Prize in physics (E. Segré, O. Chamberlain and T. Ypsilantis).

A stack of nuclear emulsions was also exposed to the negative particle beam generated by the collision of the proton beam into a target. The antiprotons were distingueshed from the produced pions using the time of flight (40 ns) for pions, vs 51 ns for pbar.

Berkeley 1955: da sin., E. Segrè, C. Wiegand, E. Lofgren, O. Chamberlain, T. Ypsilantis

First Antiproton Event in Emulsions

Visible Energy = 826 MeV



A new particle Detector: Bubble Chamber

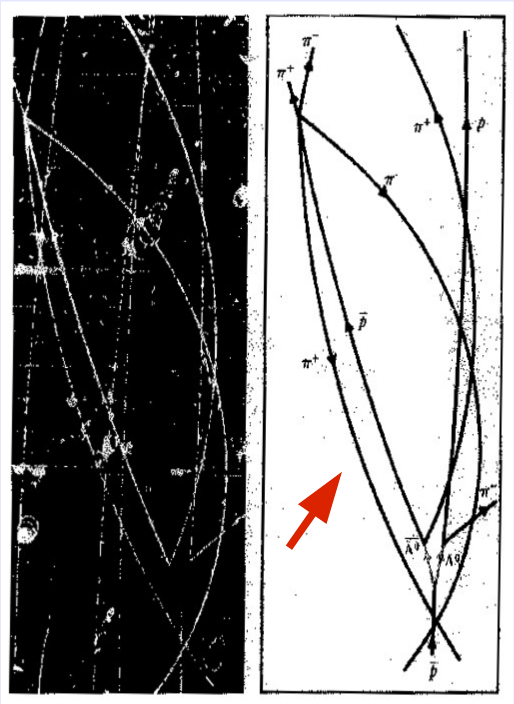
I came to LBL from the University of Rome in 1961, first working in a group that used nuclear emulsions as detector, but in 1962 I moved in the Alvarez group. The bubble chamber was the new detector installed in the newest accelerator : the Bevatron (6.2 GeV).

Both the Λ and Λ were already known. Here we see a picture of one event in the HBC: an antiproton colliding with a proton and producing a Λ and an Λ

$$\bar{p}\, p \rightarrow \Lambda\, \bar{\Lambda}$$

19 new particles were discovered in the bubble chamber. Both protons and antiprotons beams were used. Also beams of K mesons were used for searches of new particles containing a strange quark (like the K meson).

These particles were called strange because they decay in a very short time



Antiproton beam in the 72” Bubble Chamber

Hydrogen Bubble Chamber Discoveries

Resonances: 8 by the LRL (now LBL) group, 10 co-discovered by LBL or by groups who used the LBL film

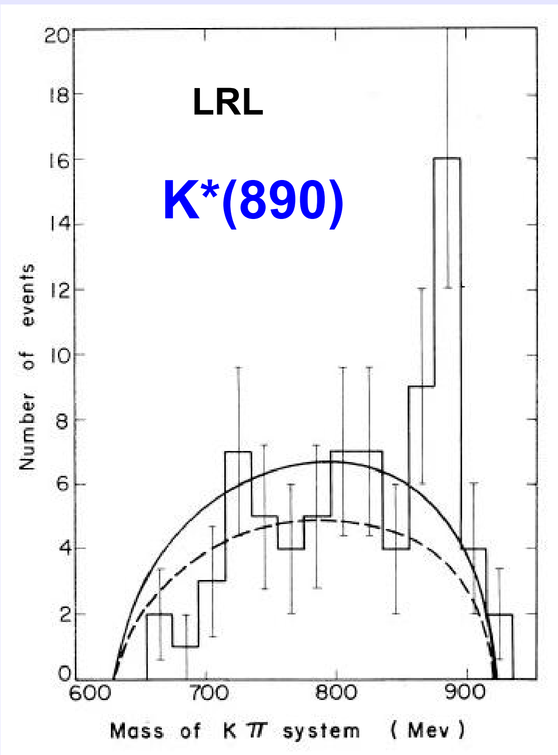
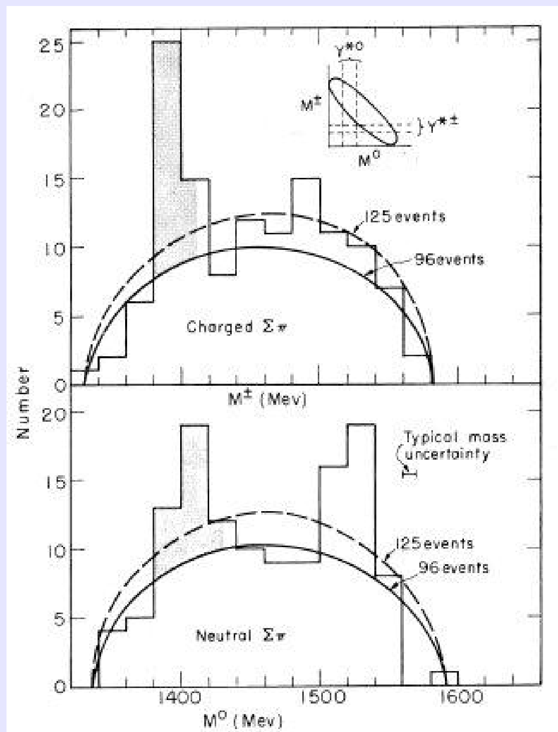


Fig. 15. – Discovery of the K*(890).

Σ(1385) and Y*^{0}(1405)

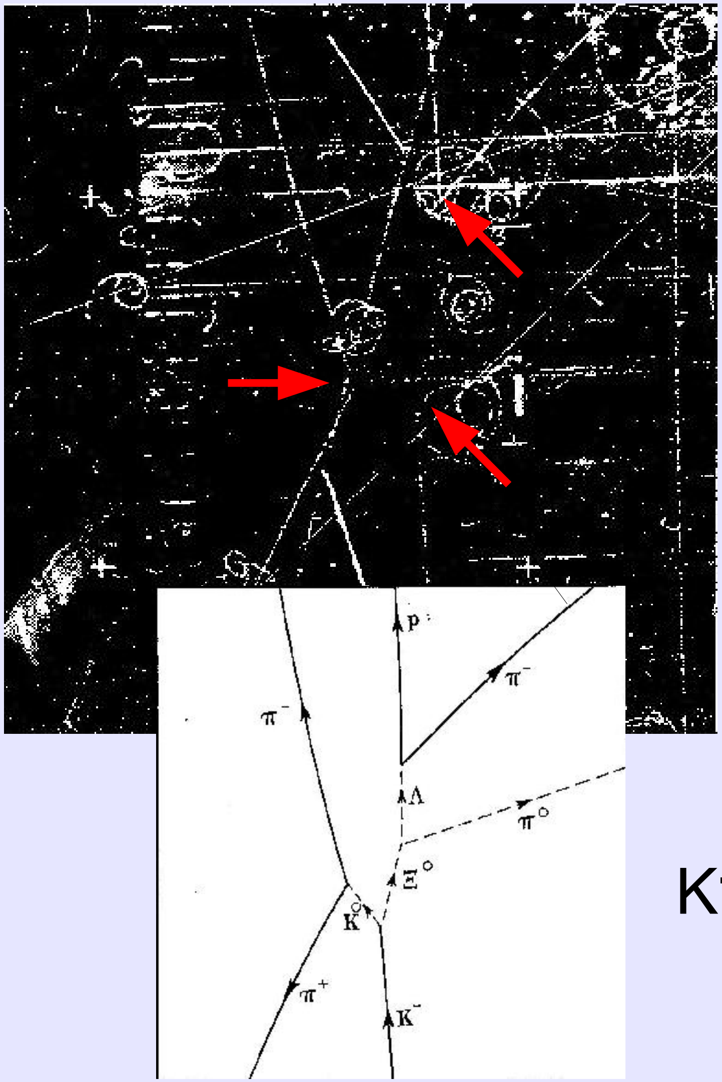


Y*(1385)	baryon	LRL	1960
K*(890)	meson	LRL	1960
Y*(1405)	baryon	LRL	1960
ρ meson		BNL+ LRL	1961
ω meson		LRL	1961
η meson		JH/NW +LRL	1961
Y*(1520)	baryon	LRL	1962
φ(1019)	meson	BNL/SY/UCLA	
Y*(1660)	baryon	LRL	1962
X*(1530)	baryon	UCLA/BNL/SY	
Y*(1765)	baryon	LRL	1963
A1 meson		GT +LRL	1964
A2 meson		GT +LRL	1964
η' meson		BNL/SY+LRL	1964
D(1285)	meson	LRL	1965
X*(1815)	baryon	EUC+LRL	'65
Y*(2100)	baryon	BNL+LRL	'66
Y*(2030)	baryon	BNL+LRL	'66

Alston et al.

Ξ^0 DISCOVERY

March 1959   15” Bubble Chamber



Nishijima and Gell Mann had predicted the Ξ^0 existence

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

6 Scientists ‘Trap’ New Particle Of Atom After 70,000 Photos

By ROBERT K. PLUMB

American scientists have reached a major landmark in the exploration of inner space.

A team of six at the University of California, after working a year and a half with the nation's most powerful scientific instrument, the Bevatron, has obtained a ghostly picture of the atomic particle called the Xi zero.

The Xi particle has zero electrical charge. So it left no tracks to be photographed in experiments in which known atomic particles were traced as they plunged through a tank of liquid hydrogen.

But the presence of one Xi zero particle has been deduced from ghostly effects in a photograph that shows the motions of known particles to be peculiarly skewed by "something." The something in the photograph is the Xi zero particle.

An Xi zero, according to the new evidence, weighs abou 2,570 times as much as an electron, and it has a lifetime o about one ten-billionth of a second.

Seventy thousand photograph were taken to catch one Xi zer in motion. A photograph take just before Christmas has bee identified after rigorous analysis as a genuine Xi zero ghos track. The finding will be published in Physical Review Letters, a publication of the American Physical Society.

Mathematical calculations tw years ago by Dr. K. Nishijima a Japanese physicist, and Dr Murray Gell-Mann of the California Institute of Technology predicted that the Xi zer should exist. The new photograph proves it, the Universit of California team reported.

An Xi zero is one of thirt

Continued on Page 28, Column

The New York Times
Published: March 5, 1959

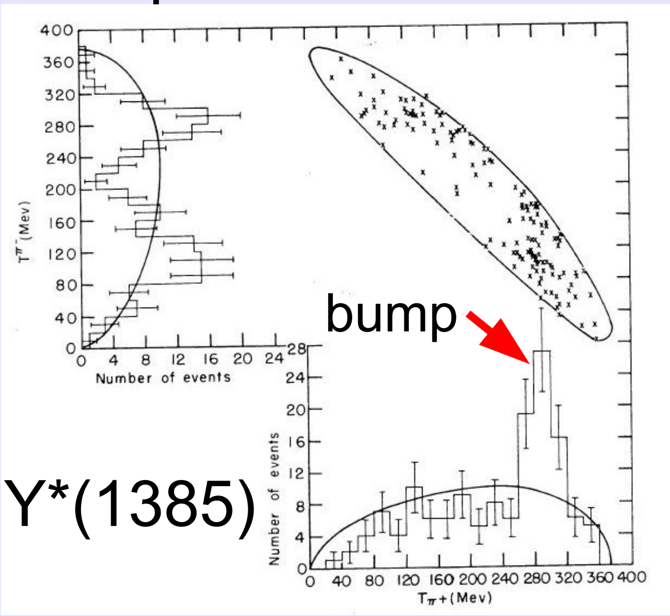
RESONANCES

The Λ and the Ξ^o seen earlier have a lifetime of $\approx 10^{-10}$ sec.
They decay into other particles, and we can see a gap in the film.

A new class of particles, the resonances, decay in a very short time (10^{-23} seconds), no gap is seen.
The resonances are found by a peak in the T of a particle in the event.

Here is the first resonance seen in HBC
by "Bump Hunting".
Discovery by:
Alston, Alvarez, Eberhard, Good, Graziano, Ticho,Wojcicki

$K^- p \to \Lambda\, \pi^+ \pi^-$



Only one resonance Δ++(1232) -> proton+pi+ was known before the HBC were constructed.
This was discovered by the Fermi group at Chicago (1952).

1968 Nobel Price

Luis Alvarez won the Nobel Prize in Physics In 1968

" … for his contribution to particle physics …with the development of the hydrogen bubble chamber and data analysis "

The small bubble chambers used for the discoveries. The 72" is partially shown here.

Lina Galtieri and Luis Alvarez in 1977

Luis invited his closest collaborators to go to Stockholm with him to participate to all activities associated with the Nobel Prize. We were among the eight couples that went with him and his family

The Birth of the Quark Model

Which particles were known in 1950?
Proton, neutrons, electrons, that comprised the atom
Leptons(light particles): electrons, muons, neutrinos
Hadrons(heavy particles):proton, neutrons

What about all these new particles? Can we find a way to classify them with a few building blocks?
Gell-Mann chose the whimsical name of “quarks” for these constituents. This word appears in the phrase “three quarks for Muster Mark” in James Joyce’s novel Finnegan’s Wake. It was also called ‘The eightfold way’, a saying of the Budda about the eight ways to reach Nirvana.’
The same scheme was suggested by Yuval Ne’eman.

Murray Gell-Mann

The quarks required a charge +2/3 and -1/3 of the charge of the proton. No fractionally charged objects had been observed, so this was a revolutionary suggestion. At first the quarks were regarded as a mathematical fiction, but experiment have convinced physicists that quarks do exist. Zweig came up with the same model. The 1969 Nobel Prize was awarded to Gell-Mann and Zweig

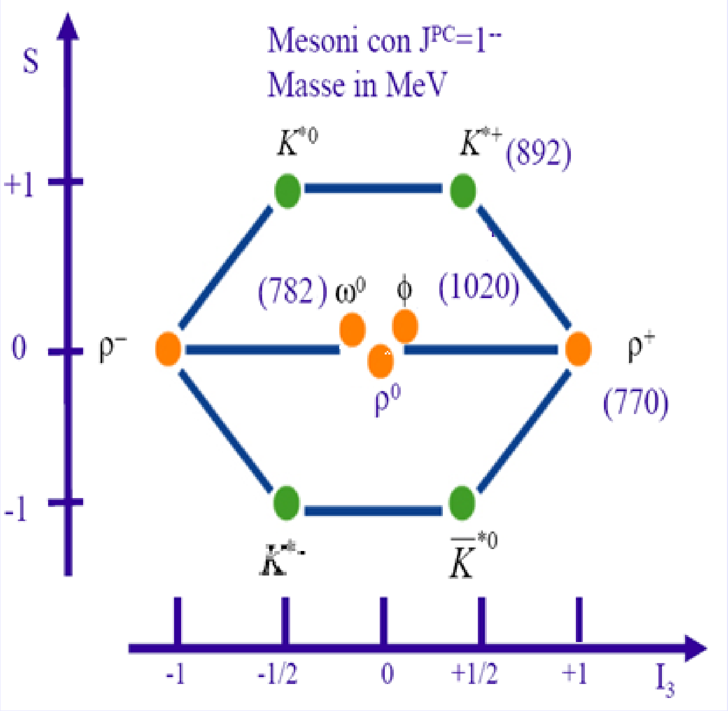
THE JP=1$^-$ MESON NONET

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$\mathbf{u\bar{d}}$	+1	0.140	0
$\mathbf{K^-}$	kaon	$\mathbf{s\bar{u}}$	−1	0.494	0
ρ^+	rho	$\mathbf{u\bar{d}}$	+1	0.776	1

π+ and ρ+ have the same quark content, but different spins

Mesons are made with two quarks.

This entire nonet was discovered (K*,ω) or co-discovered (ρ, ϕ) in Luie's bubble chambers.



BARYON MULTIPLETS

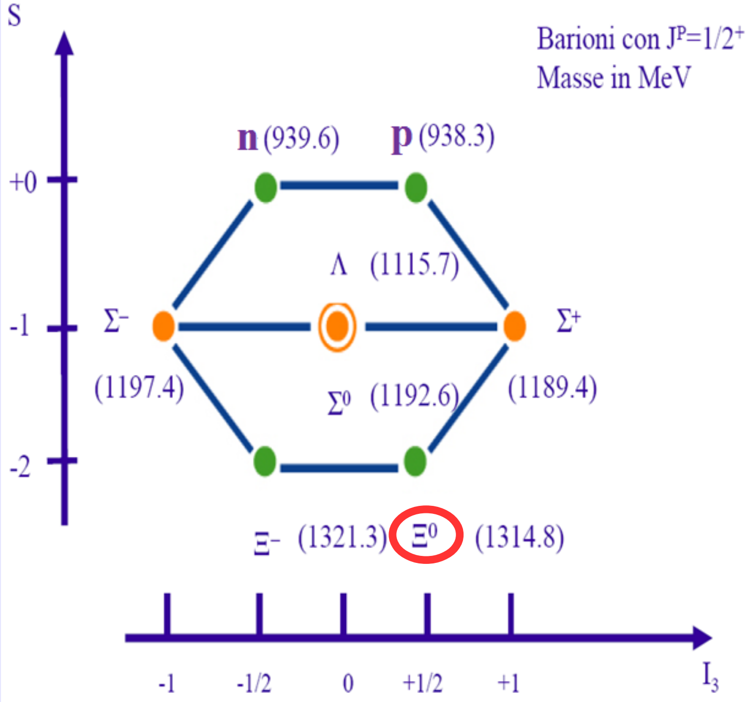
Baryons are made of three quarks.

proton

SU(3) algebra expects:

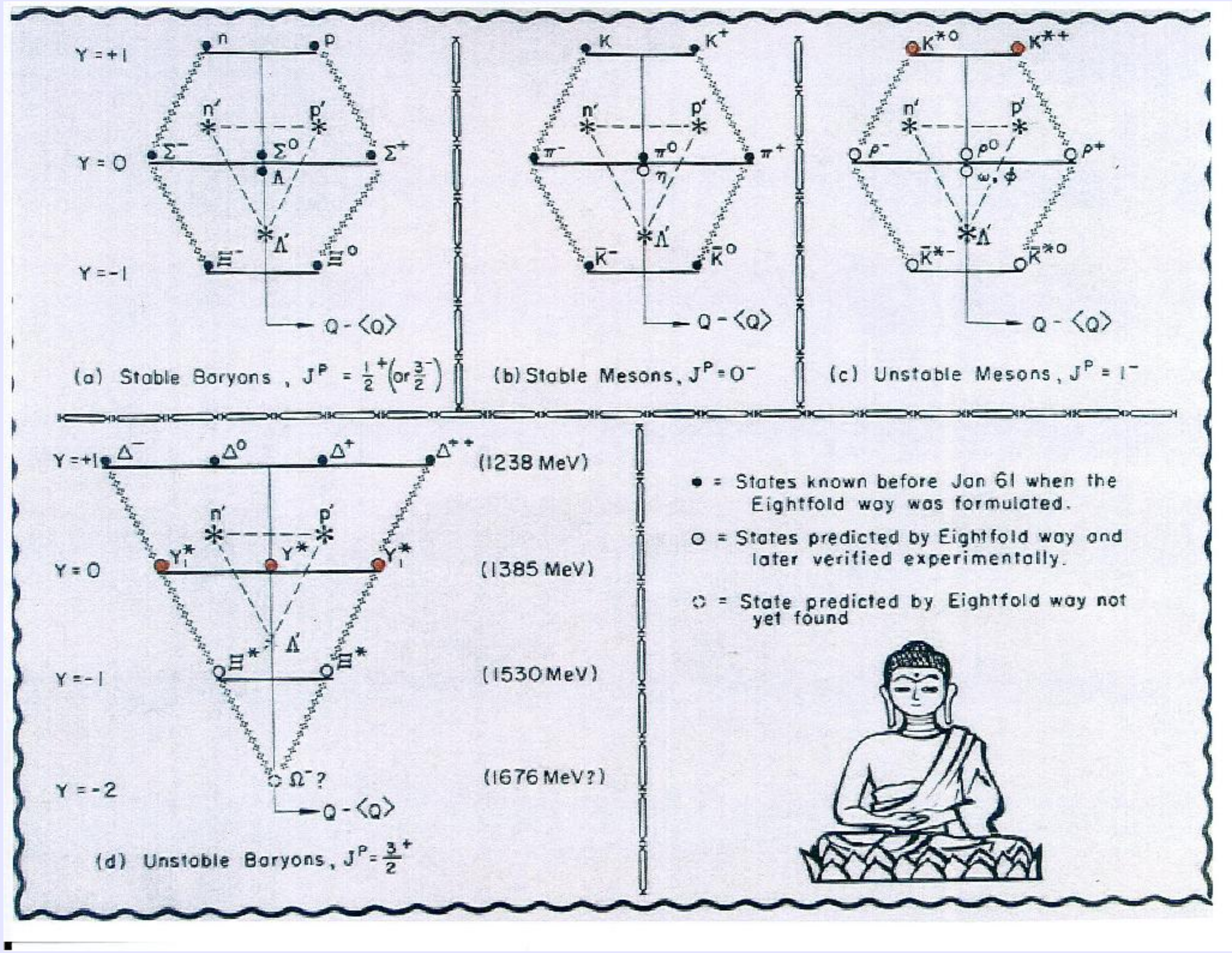
$3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$

JP=1/2+ Baryon nonet



Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	antiproton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Baryons and Mesons



The omega was discovered in 1964.
Its mass is
M= 1672 MeV

Too heavy to be seen at LBL.

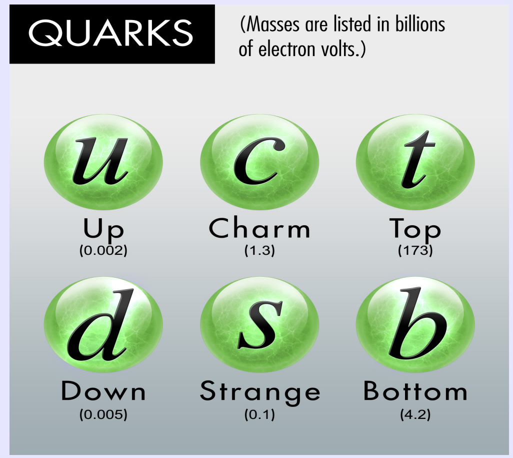
SU(3) complete!
u d s

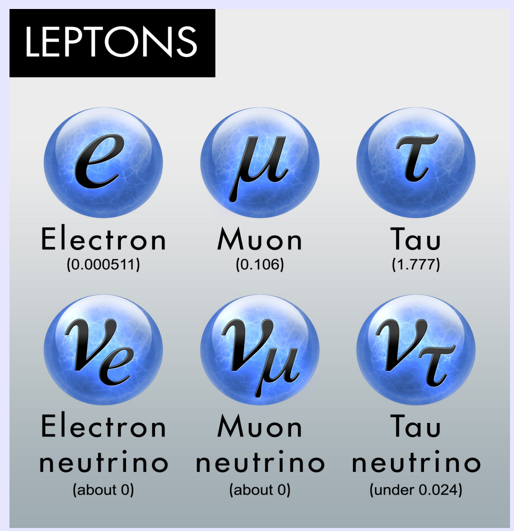
Standard Model

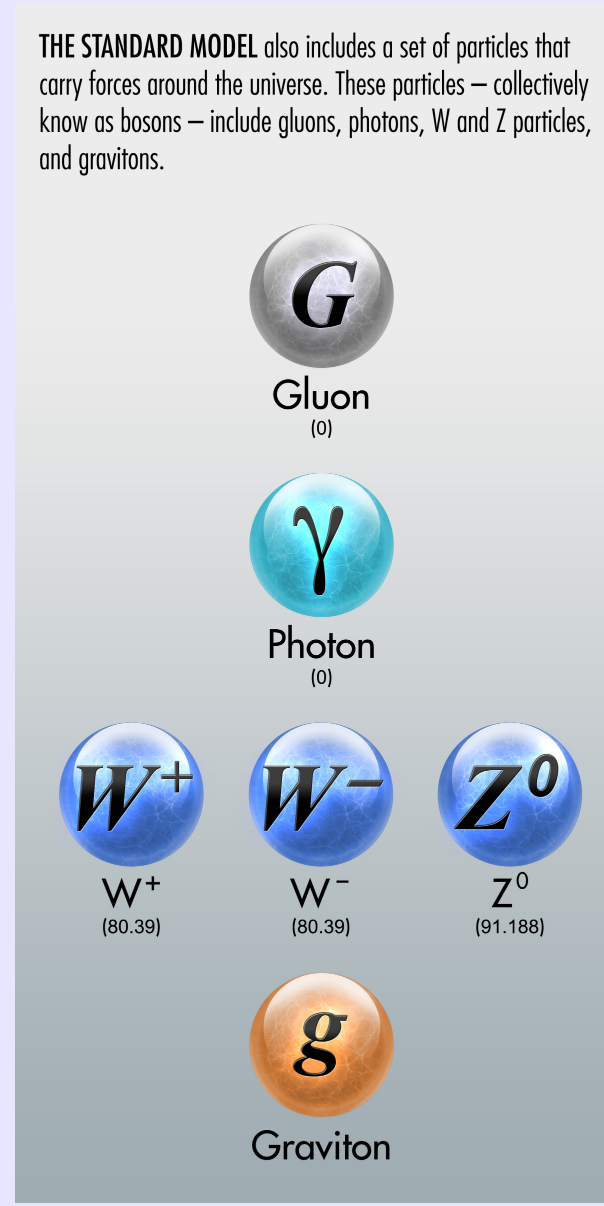
1967-1970: Glashow, Weinberg and Salam hypothesized the Standard Model, unifying all that we knew at the time:
QED (e.m.),
Weak interactions (W,Z)
Strong interactions (Gluon)

They received the 1979 Nobel Prize

Glashow, xxxx, Rosenfeld

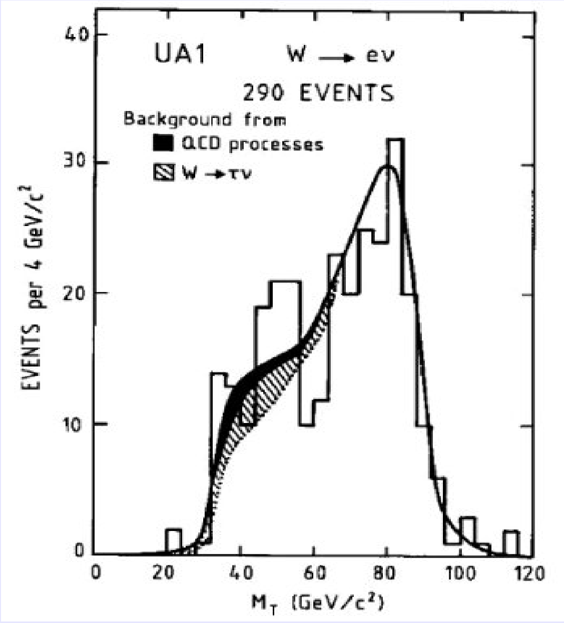


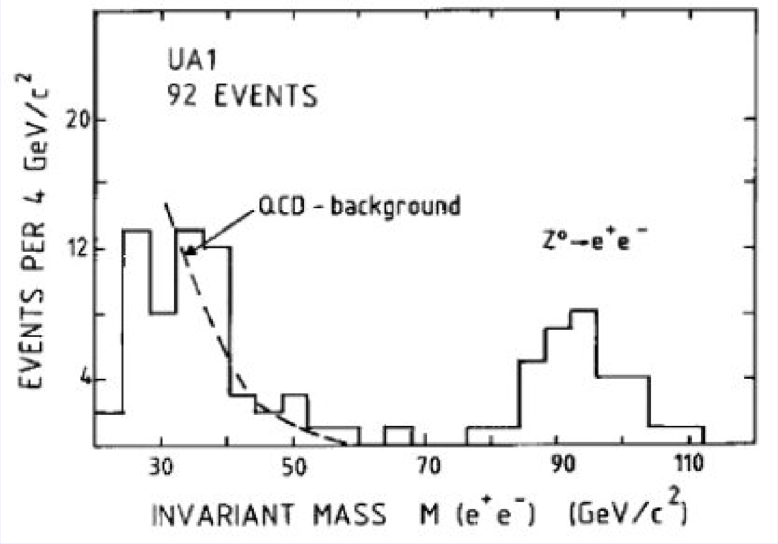




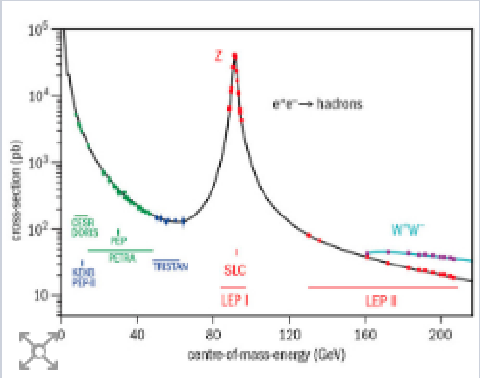
Discovery of W and Z (the force carrier)

At CERN Rubbia found the W and Z in 1973.
Carlo Rubbia was working at FNAL on the p-pbar collider, but the energy was not sufficient to discover the W and the Z.
He went to CERN and got the funds for a collider there, thus found both the W and Z!
Rubbia received theNobel Prize in 1984





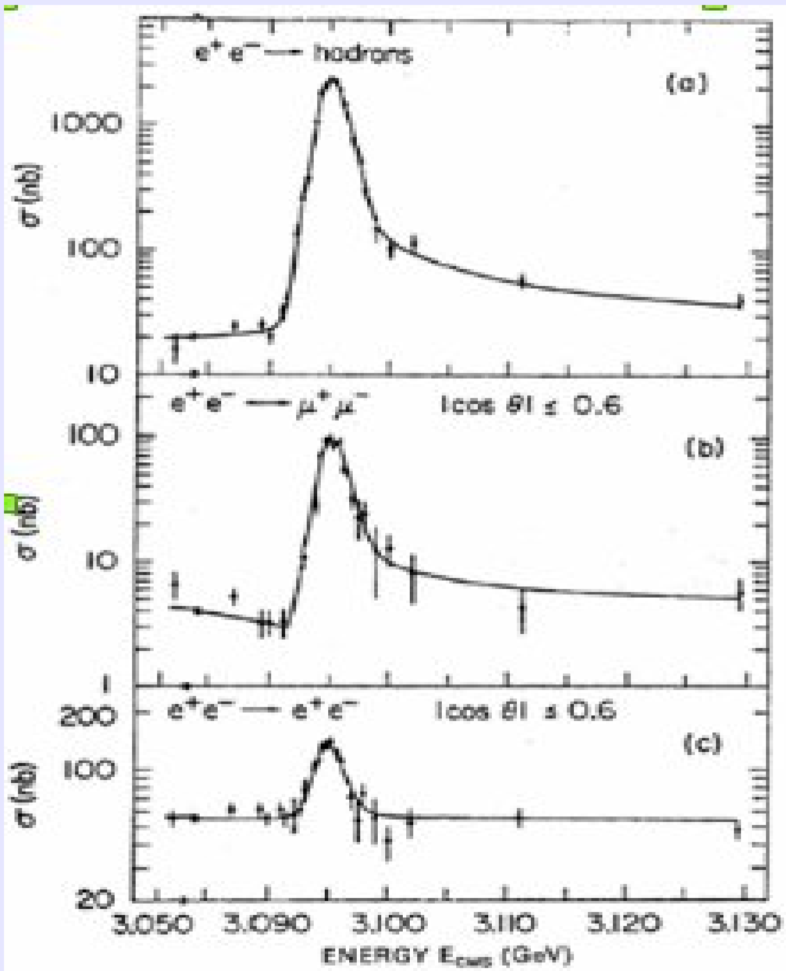
Bumps on the particle-physics road



The Z boson is the most precisely measured resonance in particle physics, with the LEP collider in particular confirming its mass and width.
Image credit: arXiv:hep-ex/0509008.

Discovery of the charm quark

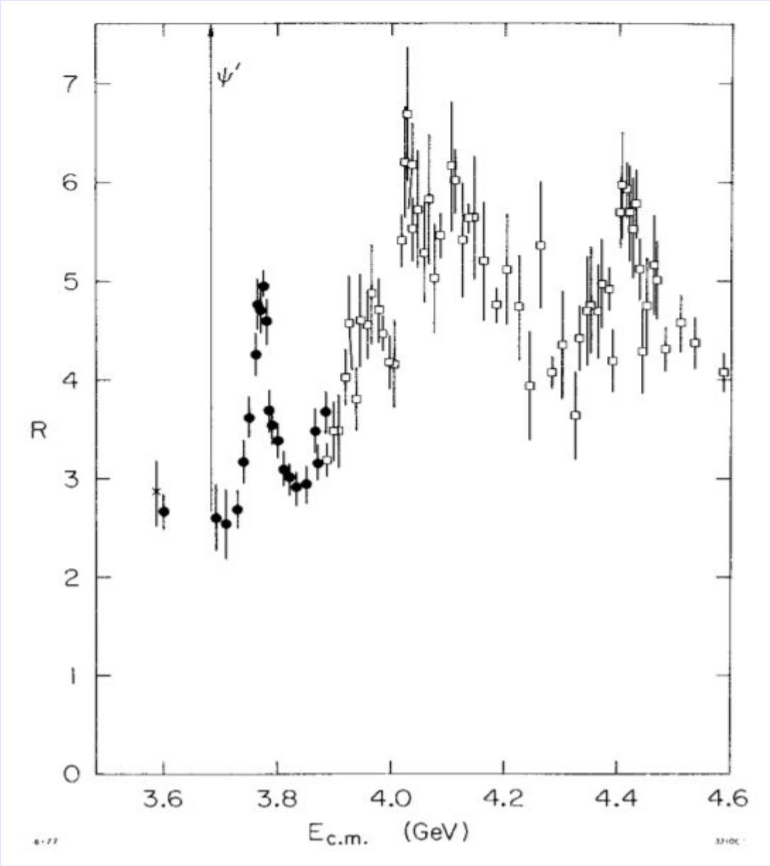
So far we have dealt with 3 quarks, (SU(3)), but eventually the number of quarks will go up to 6, including the top quark



Charm discovered at SLAC on November 11-1974
and at BNL by Sam Ting. The 3 peaks are due to a c-cbar bound states

Bert Richter and Sam Ting were awarded the Nobel Prize for the charm quark discovery in 1976

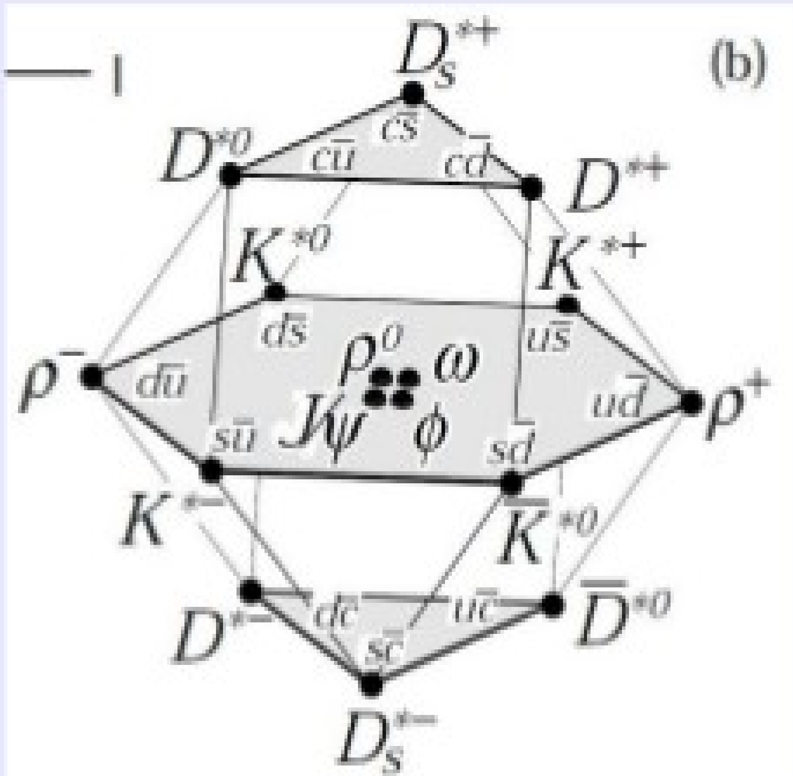
More charm



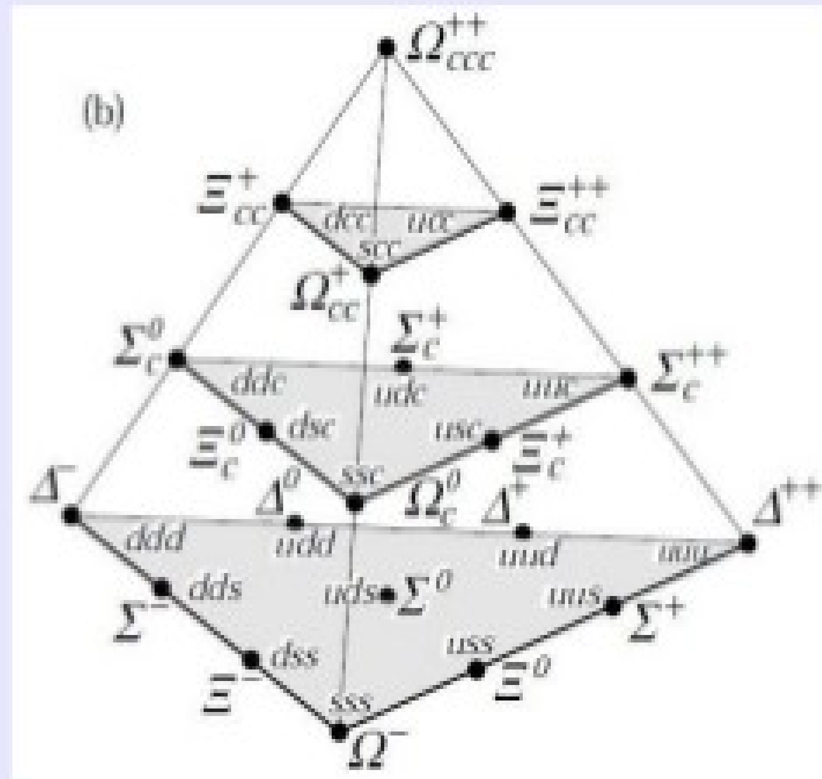
The SLAC e+ e- machine collided the beams at higher energy and new peaks showed up: the first sharp one, is due to open charm, i.e, the production of a pair of charmed mesons: D0 and D0bar.

Meson and Baryons from udsc quarks

Mesons with d u s c quarks



Baryons with d u s c quarks



More multiplets containing the b quark have been discovered

The tau lepton: the LeadGlass Wall

The tau lepton was observed at SLAC in 1975, in the Mark I detector
the same detector where the charm quark was discovered.

For the tau lepton was necessary to identify events with e or mu. Better electron identification was needed. A lead glass detector served the purpose. The tau lepton was confirmed in 1977

Martin Perl got the 1995 Nobel Prize for the discovery of the tau lepton

(Barbaro-Galtieri et al. 1977b). The abstract read:

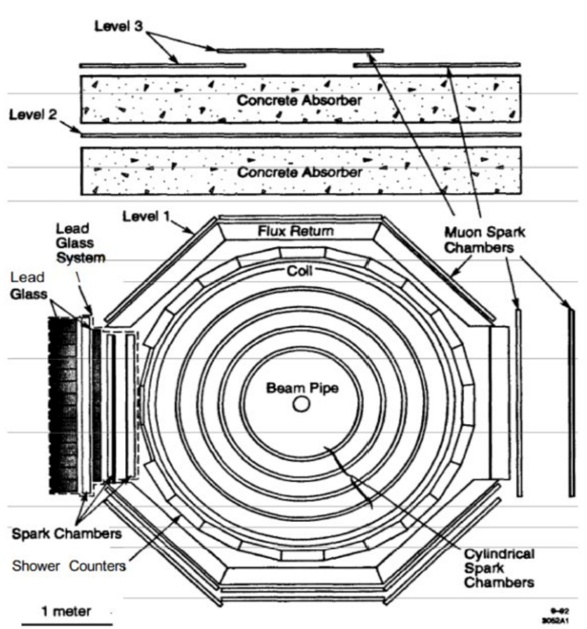
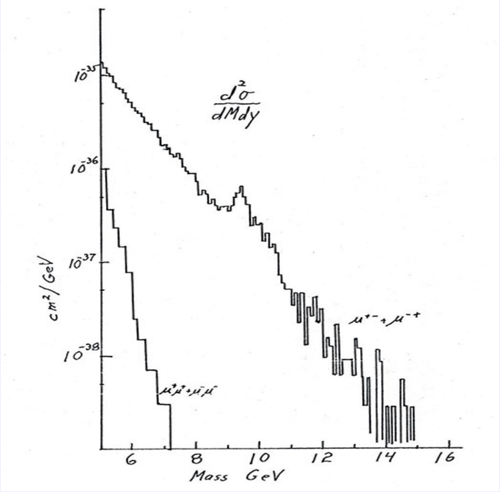


Figure 9. The "lead glass wall" modification of the Mark I detector used at SPEAR to find anomalous electron events.

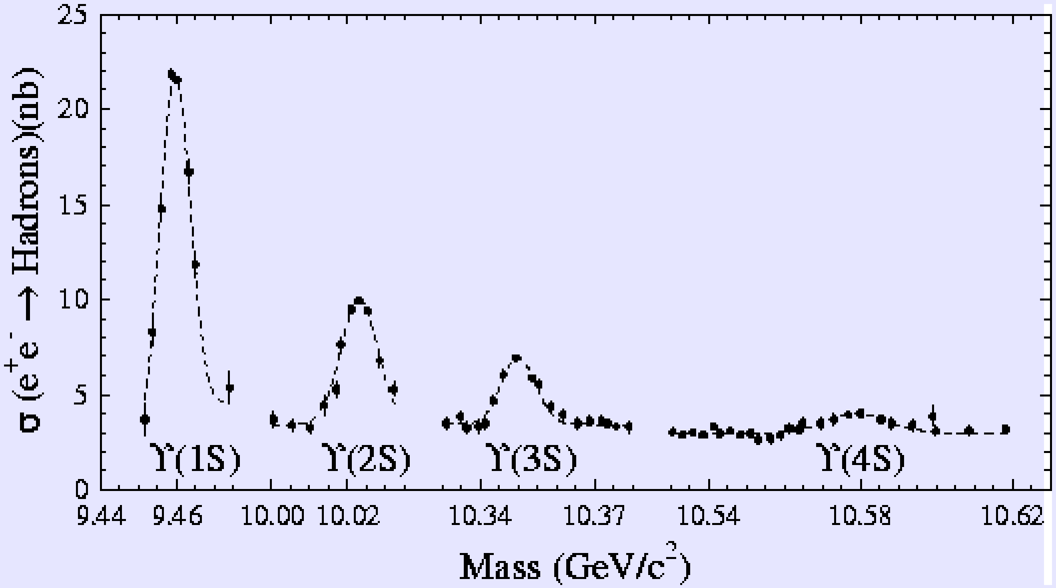
Discovery of the b quark (1977)



The bottom quark was found a Fermilab.

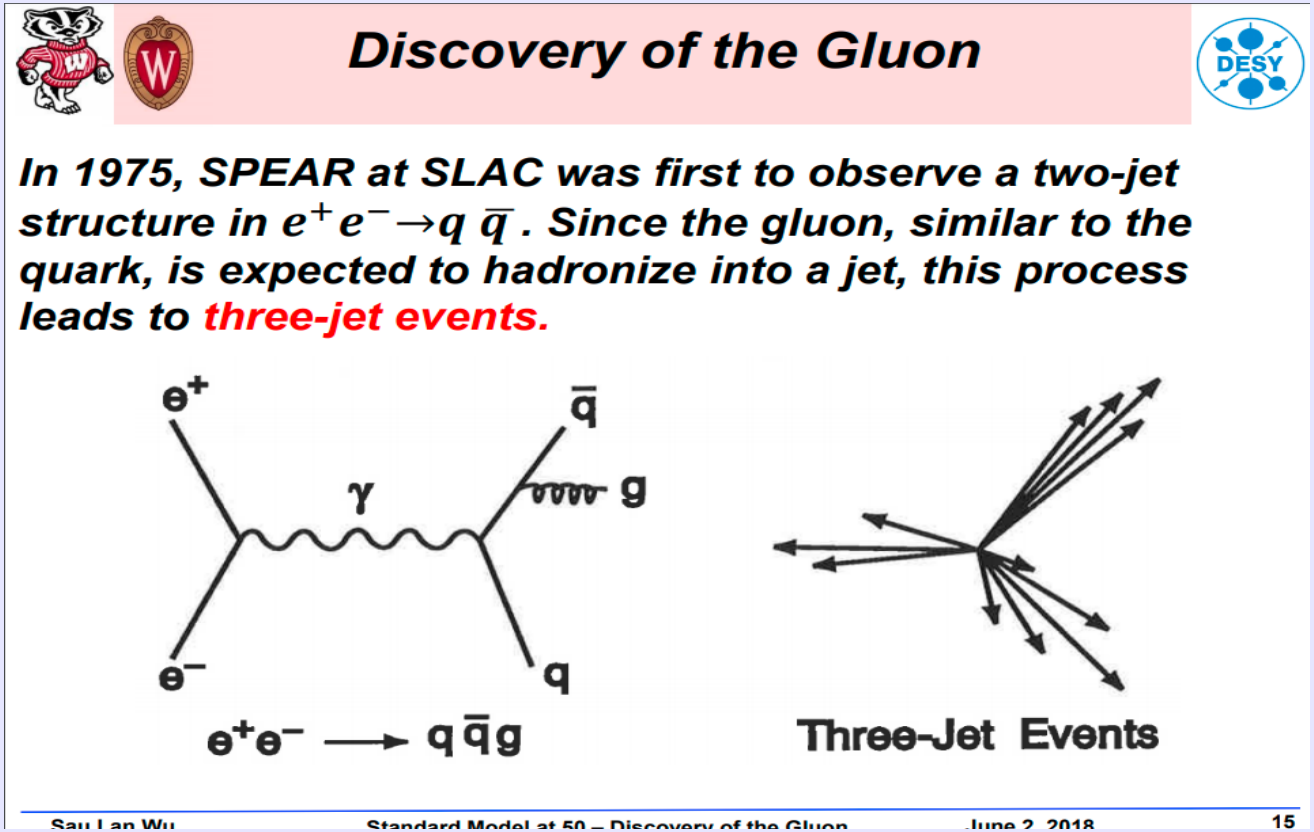
Lederman's group found many bound states of b and b-bar like the charmonium states

The 1988 Nobel Prize was awarded to Lederman



Discovery of the gluon

At this point most of the standard model elements had been seen. The gluon and the top are missing.



The gluon was discovered in 1979 at DESY by the TASSO Collaboration. They used the PETRA collider operating at 27.4 GeV.

Missing quark (the top)

The Standard Model

- Leptons

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \quad \begin{matrix} Q \\ 0 \\ -1 \end{matrix}$$

- Quarks

?

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \quad \begin{matrix} +2/3 \\ -1/3 \end{matrix}$$

- Gauge Bosons
  Mediators of the fundamental forces

		Q	M	Spin	
e.m.	γ	0	0	1	QED
weak	$W^{\pm}$	± 1	80 GeV	1	Weak
	Z^0	0	90 GeV	1	
strong	g	0	0	1	QCD

Masses very different $\rightarrow$ broken symmetry
$\rightarrow$ Higgs Mechanism

TOP SEARCHES

1. e^+e^- colliders
   - Tristan (1988) $M_{top} > 28$ GeV
   - SLAC, LEP (1990) $M_{top} > 44.8$ GeV
2. Hadron Colliders (this talk)

1983-1985

- CERN $p\bar{p}$ collider ($\sqrt{s} = 546, 630$ GeV)
  – 0.7 pb^{-1} - collected by UA1 $\rightarrow$ M_{top} >41 GeV

1988-1989

- CERN $p\bar{p}$ collider ($\sqrt{s} = 630$ GeV)
  – 4.7 pb^{-1} - collected by UA1 $\rightarrow$ $M_{top} > 61$ GeV
  7.5 – ~~6.4~~ pb^{-1} - collected by UA2 $\rightarrow$ $M_{top} > 69$ GeV
- FNAL $p\bar{p}$ collider ($\sqrt{s} = 1800$ GeV)
  – 4.4 pb^{-1} - collected by CDF $\rightarrow$ $M_{top} > 89$ GeV

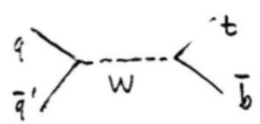
@ 95% CL

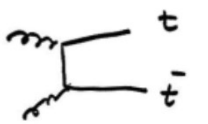
Where is the top ?

LG talk at DESY (October 1-1990)

I. INTRODUCTION

- Top Production (in lowest order)





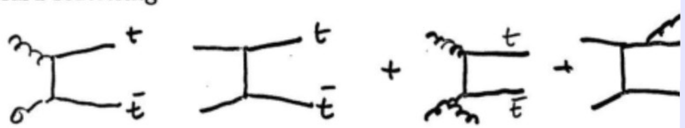
electroweak
$m_t < m_W + m_b$
dominant at CERN energies

hard scattering
dominant at Tevatron
even for $M_t \sim 60$ GeV

- Will discuss
  a. Rates
  b. Topology
  c. Physics Background

A. Rates

- W cross section relevant for $M_t \lesssim 70$ GeV
  - Calculated by Altarelli et al. in higher order QCD
  - Measured at both CERN and FNAL
- Hard scattering

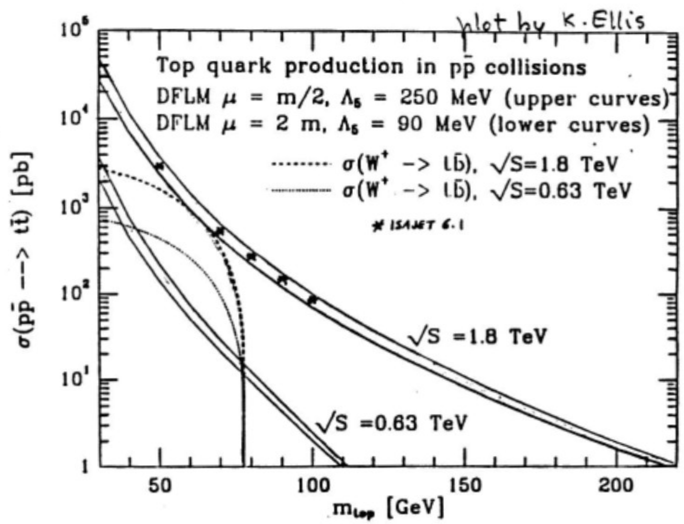


Higher order calculations done by Nason, Dawson and K. Ellis [NP. B303, 607 (88)] - K factor for top $\lesssim 1.5$.

5.

- Top cross-sections calculations by Altarelli et al (NP B303, 1988)
  using: Nason, Dawson, Ellis — α_s^3 calculation
  Diemoz, Ferroni, Longo, Martinelli: higher order structure functions

obtain, after variation of Λ_s, Q^2 scale)
$d\sigma \sim \pm 30\%$



- Note that this uses only 1 set of structure functions. Uncertainty can be larger
- Note that at 1.8 TeV
  hard process dominates over the electroweak

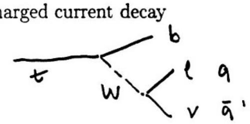
Top Decays

LG talk at DESY (October 1-1990)

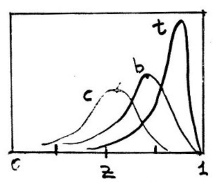
6.

B. Topology

- Standard charged current decay



- Before decaying top quark fragments into a top meson or baryon which carries most of the top quark P_T.



$$Z = \frac{P_{Hadron}}{P_{quark}}$$

Peterson fragmentation form.
F(z) peaks at high z for higher masses

- $\bar{p}p \to W \to t + \bar{b}$
  - $\hookrightarrow q\bar{q}'b$
  - $\ell\nu b$
- $\bar{p}p \to t\bar{t}$
  - $\hookrightarrow q\bar{q}' b$
  - $\hookrightarrow \ell\nu b$

Hadrons →	$b\bar{b} + 2jets$ 66%		$b\bar{b} + 4$ *jets*	44%
1 *lepton*	$b\bar{b} + \ell\nu$	3×(11)%	$b\bar{b} + 2$ *jets* $+ \ell\nu$	3(14)%
2 *leptons*			$b\bar{b} + \ell_1\nu_1\ \ell_2\nu_2$	3(2.5)%
			$b\bar{b} + \ell\nu + \ell\nu$	3(1.25)%

- QCD background too large for all jets final states. Need at least one lepton as signature.
  - lepton tends to be isolated because of large M_{top}

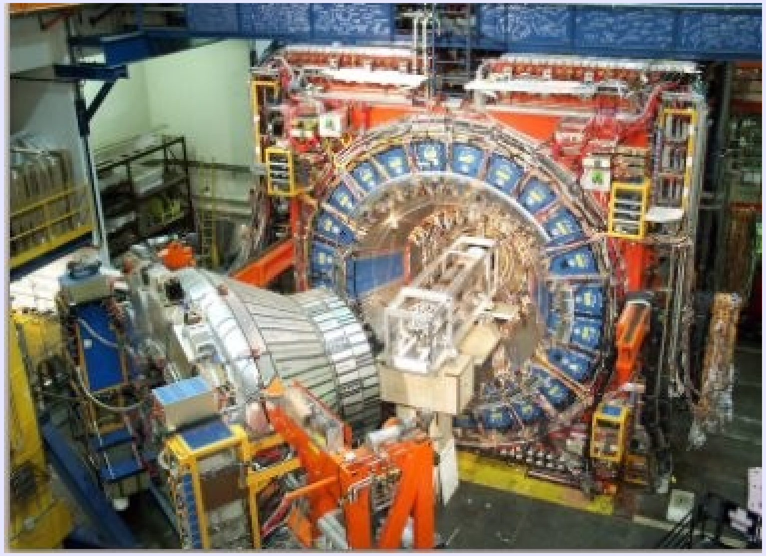
Apologies to my D0 colleagues.
At LBL there were two different groups working at FNAL in the top search.

I can only talk about the search in the CDF collaboration. The results from the D0 collaboration will be shown at the end.

Search for the top Quark

A lot of efforts went into improving the detectors and the trigger system at CDF and D0 (LBL was partecipating to both experiments).

A silicon vertex detector (SVX) was designed and built (Pisa and LBL) and installed in the CDF detector. This improved track reconstruction and allowed to reconstruct the top decay position.

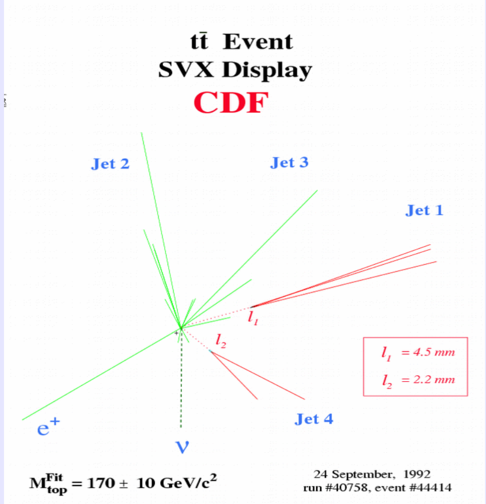


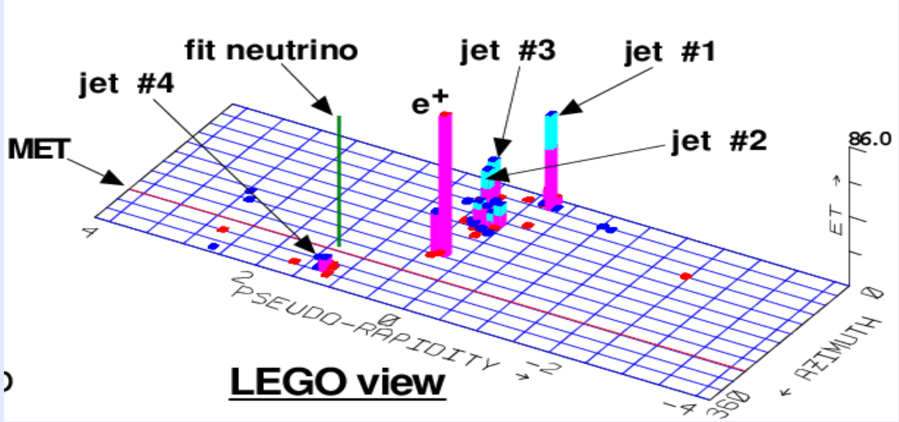
Top discovery by CDF

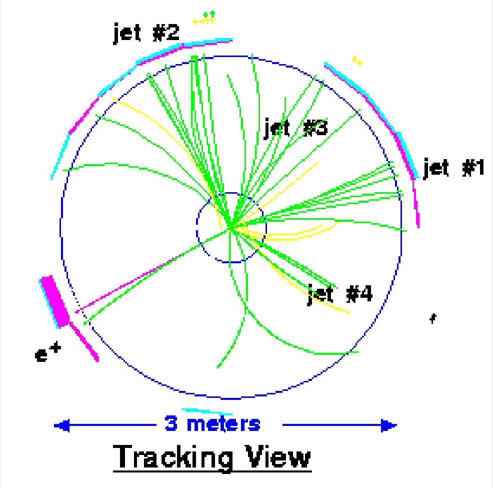
This event was found in the CDF detector on September 1992.

The reconstructions of the tracks shows the two bottom jets at a distance from the collision point

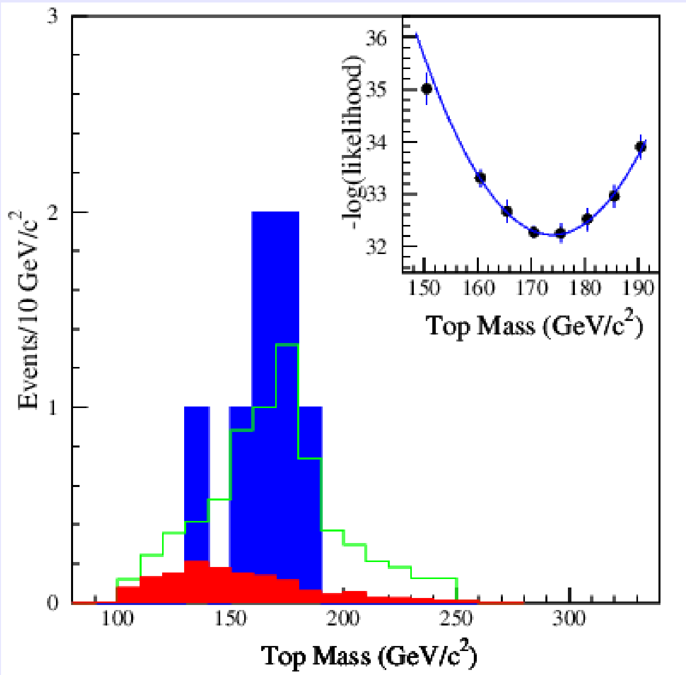
It took about 3 years before the announcement of the discovery was made. One event was not enough for the world to accept the discovery.







The CDF discovery results



Top mass distribution with 7 tagged events in run1.

M(top) = 174 ± 10 ± 12 GeV

SUMMARY and CONCLUSIONS

- We observe:

DIL : 6 events	backg.= 1.3±0.3	P=3×10^{-3}
SLT : 23 tags	backg.= 15.4±2.0	P=6×10^{-2}
SVX : 27 tags	backg.= 6.7±2.1	P=2×10^{-5}

total of 43 top events candidates

- Combined significance: $\mathbf{1 \times 10^{-6} (4.8\ \sigma)}$
- We observe a sharp peak and measure:

$$\mathbf{M_{top} = 176 \pm 8 \pm 10\ GeV/c^2}$$

- A simple KS test gives a probability of 2% that the mass distribution agrees with a background hypothesis
- Combined significance:

$$\mathbf{P{=}4 \times 10^{-7} (5.0\ \sigma)}$$

TOP IS DISCOVERED

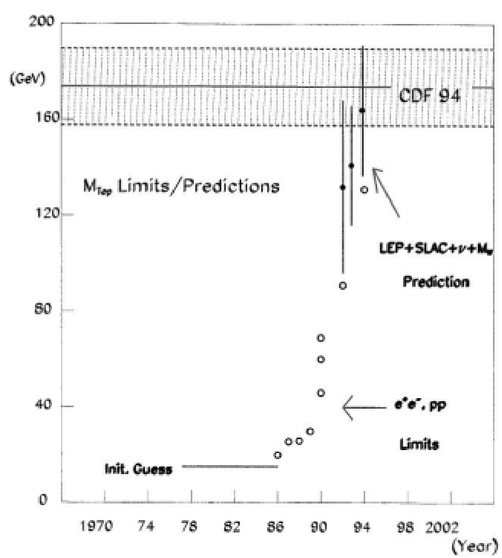
The top mass

TOP SEARCH: MASS LIMITS AND PREDICTIONS-vs-TIME

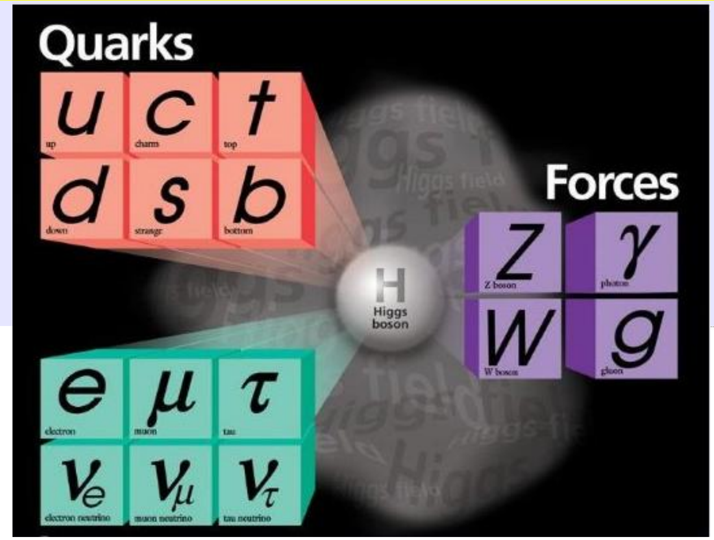
Top is finally found after many years of searches and Standard Model predictions!

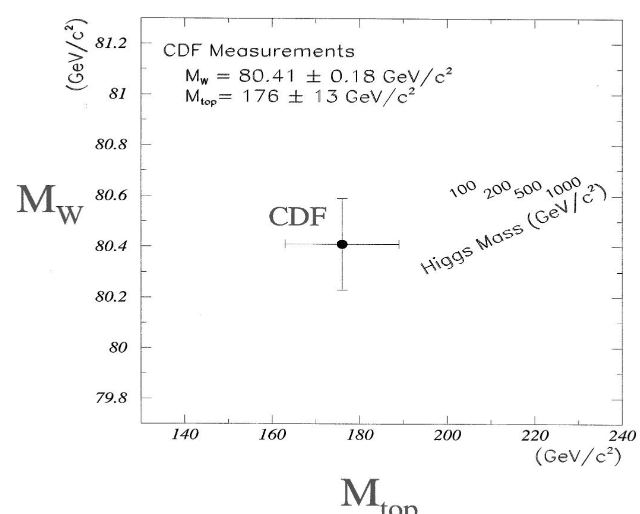
Recent Results:

$M_{top} = 176 \pm 13\ GeV/c^2$ CDF 1995
$M_{top} = 199 \pm 30\ GeV/c^2$ D0 1995



Top mass results from 1970





The error on the expected Higgs mass is very large!

The end of the story

The b quark was discovered in 1977. It took 18 years to find the top quark. The search was pursued all around the world, from Tristan to SLAC to CERN to Fermilab! Finally the top quark was found in 1995!

24 years later (on July 2019) the European Physical Society awarded to the CDF and D0 collaborations a prize for the discovery.

Some of the present and old members of the CDF and D0 collaborations