High Energy Physics

QuarkNet summer workshop

June 24-28, 2013

The Birth of Particle Physics

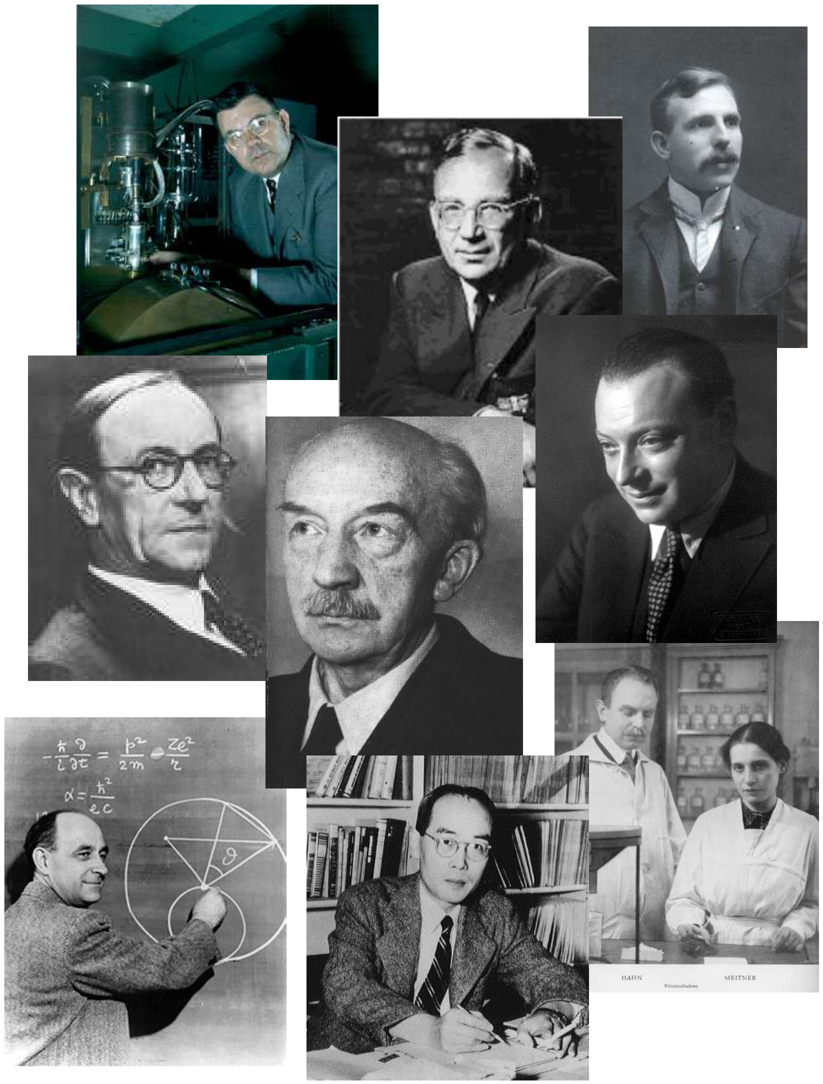
- In 1896, Thompson showed that electrons were particles, not a fluid.

- In 1905, Einstein argued that photons behave like particles.

- In 1907, Rutherford showed that the mass of an atom was concentrated in a nucleus.

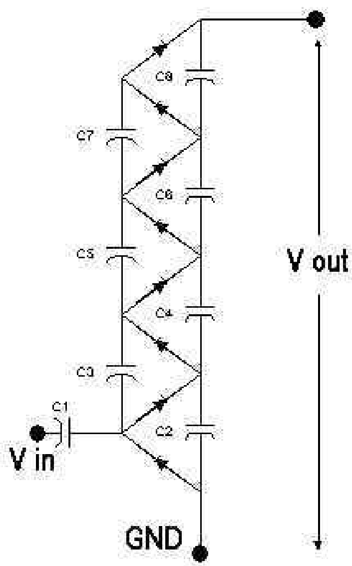
Particles that should obey the laws of quantum mechanics and relativity.

Nuclear Physics



- α, β, γ emission
- Properties of neutrons
- Fission of heavy elements
- Nuclear "chemistry"
- Nuclear forces
- Beta decay
- Neutrino postulated
- Theories of beta decay

Particle Accelerators



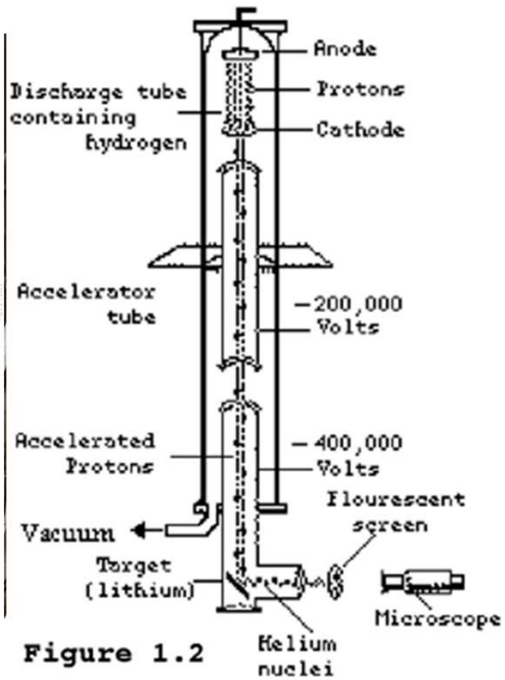
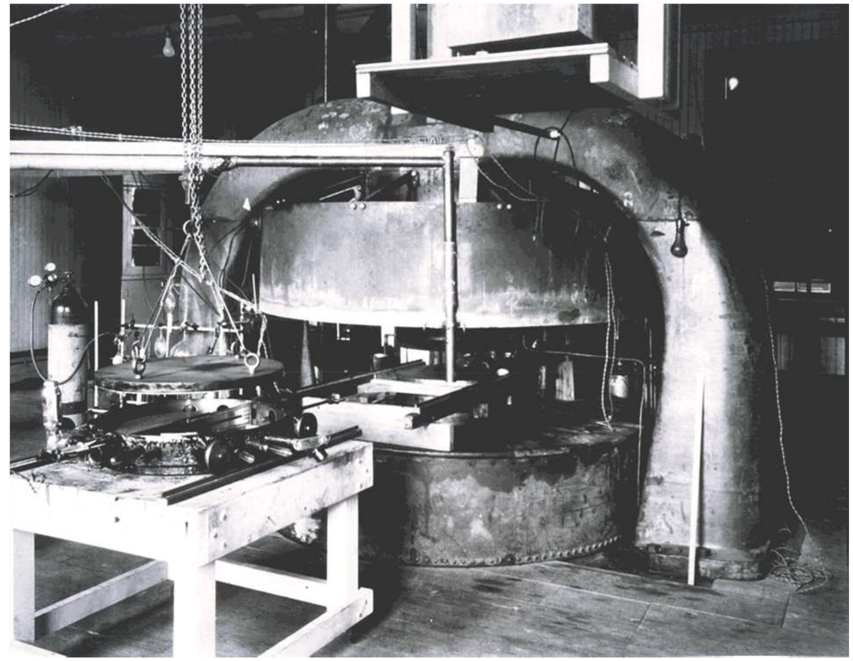
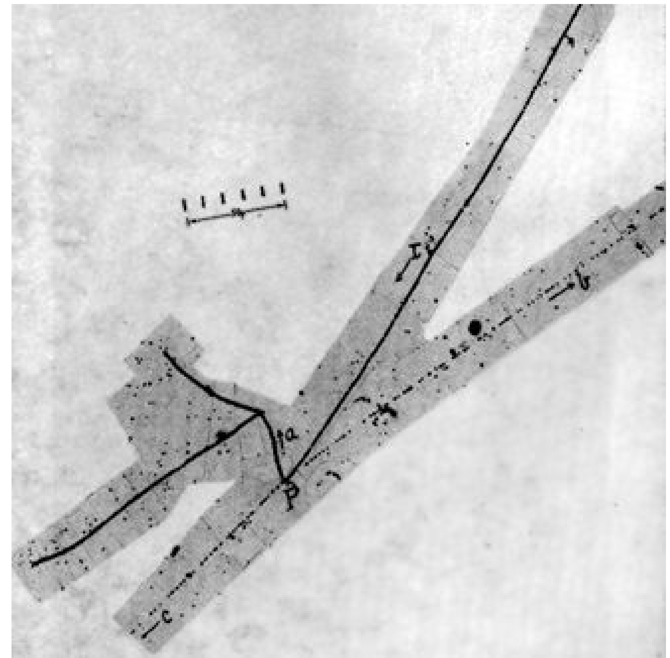


Figure 1.2



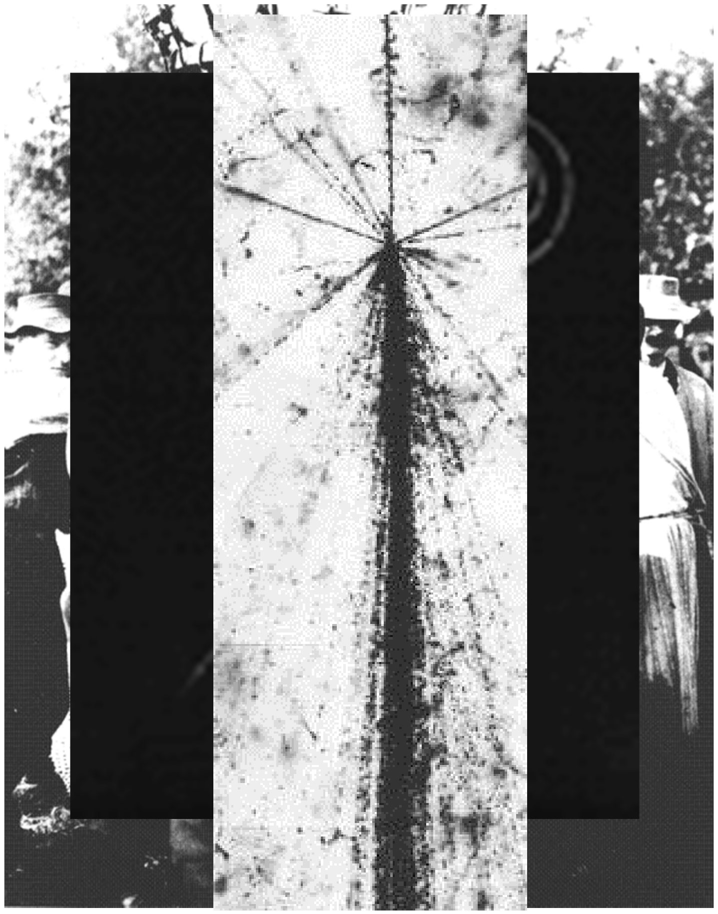
- In 1932, Cockroft and Walton accelerated protons to 600 keV, produced the reaction
  $$p + Li \rightarrow He + He$$
  and verified $E=mc^2$.
- From 1930-1939, Lawrence built bigger and bigger cyclotrons, accelerating protons to higher and higher energies: 80 keV → 100 MeV.

Particle Detectors



- In 1912, Wilson develops the cloud chamber for seeing the paths of fundamental particles
- Photographic emulsions exposed by the passage of charged particles

Discoveries in Cosmic Rays



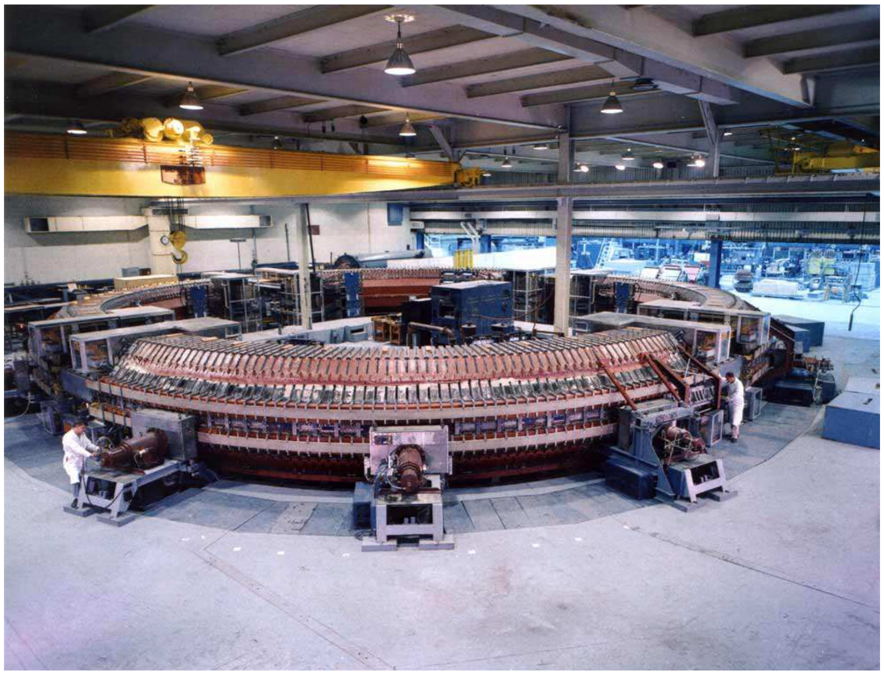
- In 1912, Viktor Hess investigated terrestrial radioactivity in balloon experiments.

- Penetrating radiation observed at high altitudes
- Solutions to Dirac’s equations interpreted as “positive electrons”
- Yukawa proposed a “meson” to explain the strong nuclear force
- Anderson observed positrons in 1932 and muons in 1936
- Perkins discovered pions photographic emulsions in 1947.

The Known Particles in 1950

symbol	particle	mass
p	proton	938 MeV$/c^2$
n	neutron	940 MeV$/c^2$
$\pi^{\pm}$	pion	140 MeV$/c^2$
$V^0, V^{\pm}$	???	???
$e^{\pm}$	electron	0.511 MeV$/c^2$
$\mu^{\pm}$	muon	106 MeV$/c^2$
ν	neutrino	0?
γ	photon	0

New Accelerators: Synchrotrons

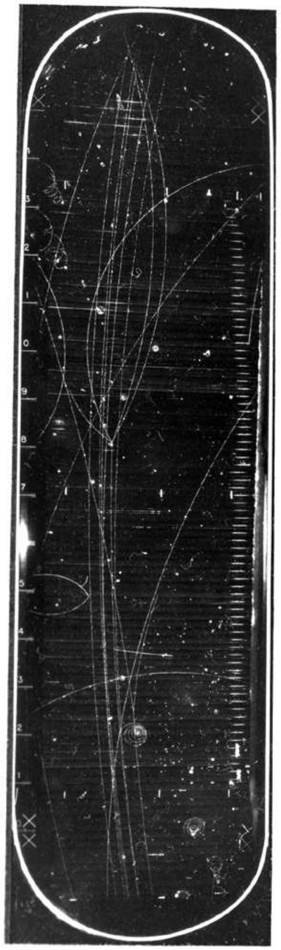


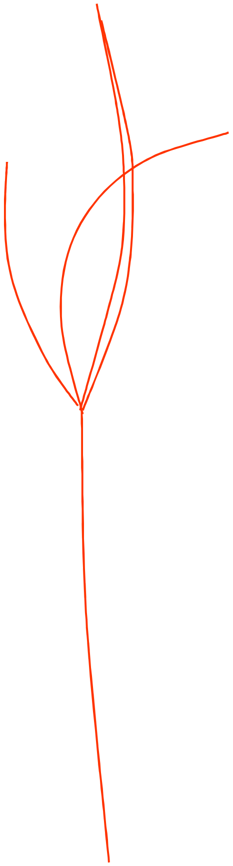
1952: Brookhaven 3 GeV "Cosmotron"

1954: Berkeley 6 GeV "Bevatron"

New Detectors: Bubble Chambers

The Berkeley 72 inch liquid
hydrogen bubble chamber





Known Particles in 1957

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}	?	?			?		

Strongly Interacting Particles: 1961

Possible resonances of strongly interacting particles (as of August 1961)

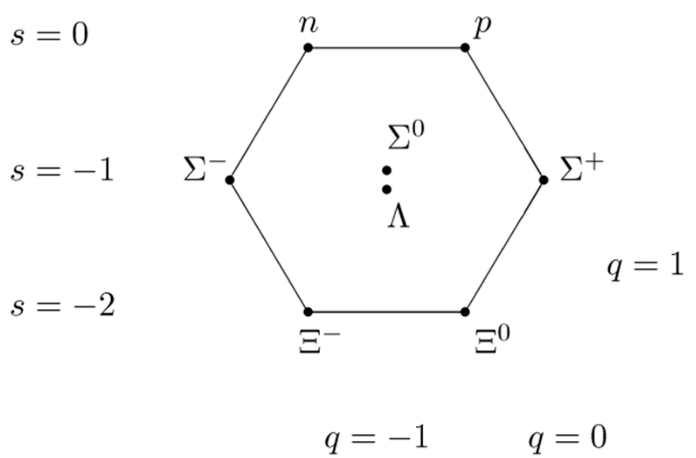
	Mass (Mev)	Half-width Γ/2 (Mev)	Spin I	Spin and parity J	Decay properties: Orbital wave	Products	Branching fraction	Q (Mev)	k (Mev/c)	Ref.
ρ	750	±50	1	1-	p	π+π	100%	480	350	a
ω	790	±<15	0	1-		3π	100%	510	——	b
K*	885	± 8	1/2?	?	?	K+π	100%	252	282	c
N*	1238	±45	3/2	3/2+	p	N+π	100%	163	234	d
	1510	±30	1/2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

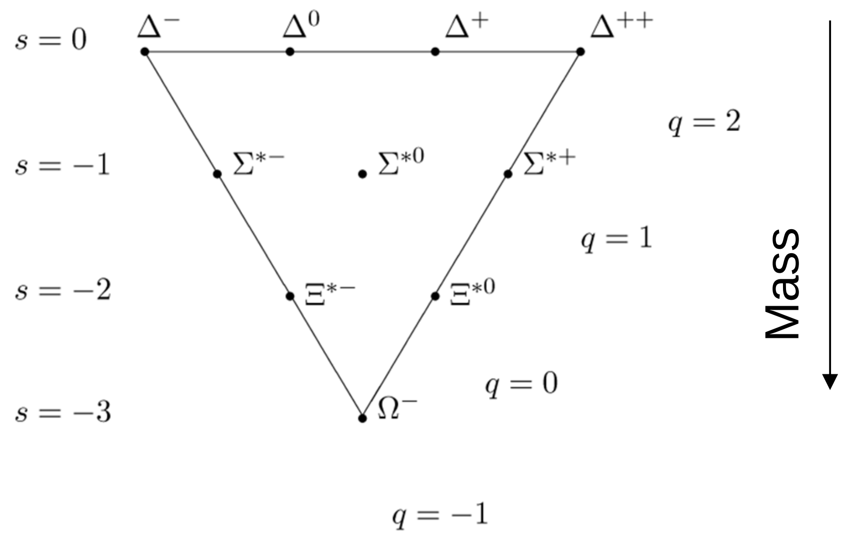
Strongly Interacting Particles: 1963

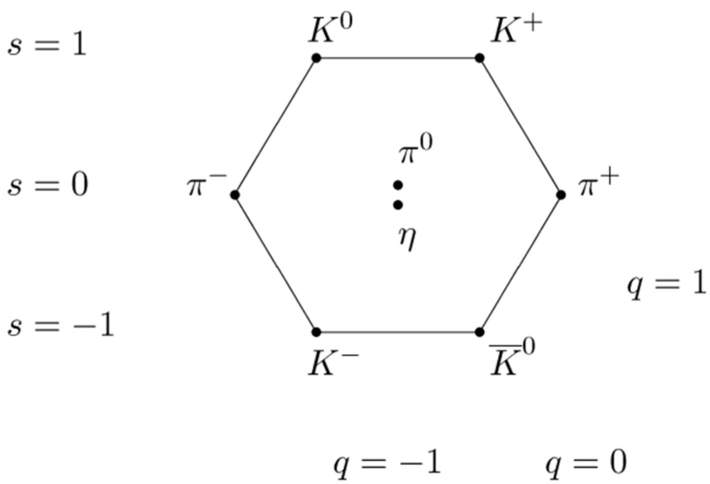
TENTATIVE DATA ON STRONGLY INTERACTING STATES (April 1963, A. H. Rosenfeld)

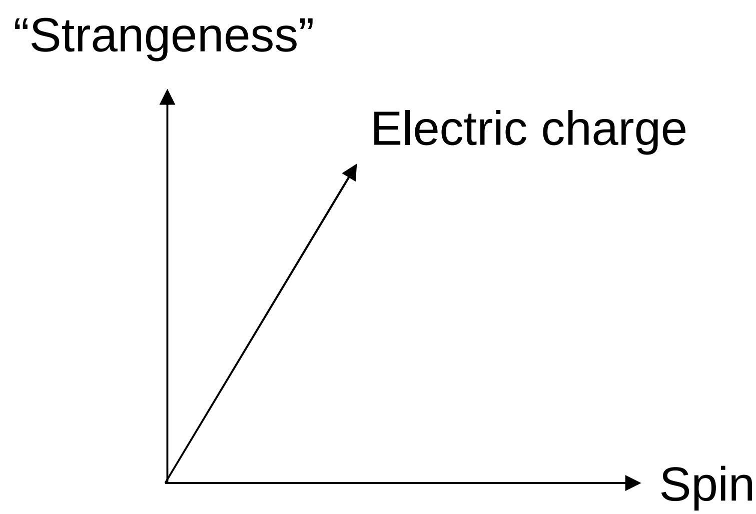
Particle	Established quantum No. $I(J^{PG})$	Possible assignment: Quantum No. $I(J^{PG})$	Possible assignment: Regge[1] trajectory	Mass (MeV)	Γ[2] (MeV)	Mass² (BeV)²	Dominant decays: Mode	%	Q[4] (MeV)	p or P_{max} (MeV/c)
K_1K_1	$0(J_{even}^{++})$	$0(0^{++})$	$+^{\omega}\alpha$	$\sim 2m_K$	?		Even number of pions $K\bar{K}(K_1K_1, K_2K_2$, not $K_1K_2)$		<0	<0
f = Vacuum ?	$0(\geq 2^{++})$	$0(2^{++})$	$+^{\omega}\alpha$	1250	75	1.56	2π 4π $K\bar{K}(K_1K_1, K_2K_2$, not $K_1K_2)$	large < 30 ?	980 710 256	690 550 380
η	$0(0^{-+})$		$+^{\omega}\beta$	548	< 10	.30	$\pi^+\pi^-\pi^0$ $\pi^0\pi^0\pi^0$[3] $\pi^+\pi^-\gamma$ $\gamma\gamma$	23 39 7 31	134 143 269 548	174 182 235 274
ω	$0(1^{--})$		$-^{\omega}\gamma$	782	< 15	.62	$\pi^+\pi^-\pi^0$[3,5] $\pi^0\gamma$ $\pi^+\pi^-$	84 12±4 4	368 647 503	326 379 364
ϕ	$0(J_{odd}^{--})$	$0(1^{--})$	$-^{\omega}\gamma$	1020	< 5	1.04	$K\bar{K}(K_1K_2$, not $K_1K_1, K_2K_2)$ Odd number of pions		24	111
$\pi \begin{cases}\pi^0\\ \pi^\pm\end{cases}$	$1(0^{--})$		$-^{\pi}\beta$	π^0 135 $\pi^\pm$ 140	0 0	0.018 .02	$\pi^0\to\gamma\gamma$[6] $\pi^\pm\to\mu\nu$	100 58	135 34	67 30
ρ	$1(1^{-+})$		$+^{\pi}\gamma$	750	100	.56	$\pi\pi$[3] (p-wave)	100	471	348
$K \begin{cases}K^0\\ K^\pm\end{cases}$	$\frac{1}{2}(0^-)$		κ_β	K^0 498 $K^\pm$ 494	0 0	.24	$K_1^0\to\pi^+\pi^-$[6] $K^\pm\to\mu\nu$	$2/3K_1$ 58	219 388	206 236
$K^*_{1/2}$ (888)	$\frac{1}{2}(1^-)$		κ_γ	888	50	.78	$K\pi$(p-wave)	100	$251(K^0\pi^-)$	283
$K^*_{1/2}$(725)	$\frac{1}{2}$(?)	?	?	725	< 15	.53	$K\pi$	?	$101(K^-\pi^0)$	161
$N \begin{cases}n\\ p\end{cases}$	$\frac{1}{2}(\frac{1}{2}+)$		N_α	n 940 p 938	0	.88	$e^-\bar{\nu}p$[6] –	100 –	.78 –	1.2 –
$N^*_{1/2}$(1688)="900 MeV πp"		$\frac{1}{2}(\frac{5}{2}+)$	N_α^{II}	1688	100	2.84	$N\pi$(f-wave) ΛK(f-wave)	80 < 2	610 76	572 235
$N^*_{1/2}$(1512)="600 MeV πp"		$\frac{1}{2}(\frac{3}{2}-)$	N_γ	1512	100	2.28	$N\pi$(d-wave)	80	$434(\pi^-p)$	450
$N^*_{3/2}$(1238)="Isobar"		$\frac{3}{2}(\frac{3}{2}+)$	Δ_δ	1238	100	1.53	$N\pi$(p-wave)	100	$160(\pi^-p)$	233
$N^*_{3/2}$(1920)	$\frac{3}{2}(\frac{7}{2})$	$\frac{3}{2}(\frac{7}{2}+)$	Δ_δ^{II}	1920	~200	3.69	$N\pi$ ΣK	30 < 4	$842(\pi^-p)$ 233	722 425
Λ	$0(\frac{1}{2}+)$		Λ_α	1115	0	1.24	π^-p[6]	67	38	100
Y_0^*(1815)	$0(J\geq\frac{5}{2})$	$0(\frac{5}{2}+)$	Λ_α	1815	120	3.29	$\bar{K}N$ $\Sigma\pi$	60 <33	383 490	541 504
Y_0^*(1405)	0(?)	$0(\frac{1}{2}-)$	Λ_β	1405	50[5]	1.97	$\Sigma\pi$ $\Lambda 2\pi$	{100}	$69(\Sigma^-\pi^+)$ $10(\Lambda\pi^+\pi^-)$	144 69
Y_0^*(1520)	$0(\frac{3}{2}-)$		Λ_γ	1520	16	2.31	$\Sigma\pi$ (d-wave) KN(d-wave) $\Lambda 2\pi$	55 30 15	$194(\Sigma^0\pi^0)$ $88(K^-p)$ $125(\Lambda\pi^+\pi^-)$	267 244 253
$\Sigma \begin{cases}\Sigma^+\\ \Sigma^0\\ \Sigma^-\end{cases}$	$(\frac{1}{2}+)$		Σ_α	1189 1193 1197.4	0 0 0	1.42 1.42 1.42	$n\pi^+$[6] $\Lambda\gamma$ $n\pi^-$	50 100 100	110 76 117	185 74 192
Y_1^*(1385)	$1(J\geq\frac{3}{2})$	$1(\frac{3}{2}+)$	Σ_δ	1385	50	1.92	$\Lambda\pi$ $\Sigma\pi$	98 4±4	$135(\Lambda\pi^0)$ $49(\Sigma^-\pi^+)$	210 119
Y_1^*(1660)	$1(\frac{3}{2})$	$1(\frac{3}{2}-)$	Σ_γ	1660	40	2.76	$\bar{K}N$ $\Sigma\pi$ $\Lambda\pi$ $\Sigma\pi\pi$ $\Lambda\pi\pi$	~10 25 30 20 15	225 335 410 200 275	406 386 441 328 394
$\Xi \begin{cases}\Xi^0\\ \Xi^-\end{cases}$	$\frac{1}{2}(\frac{1}{2}?)$	$\frac{1}{2}(\frac{1}{2}+)$	Ξ_α	? 1321	0	1.72	$\Lambda\pi^0$[6] $\Lambda\pi^-$	– –	 66	 138
Ξ^*(1530)	$\frac{1}{2}(\frac{3}{2}+)$	$\frac{1}{2}(\frac{3}{2}+)$	Ξ_δ	1530	<7	2.34	$\Xi\pi$	100	$74(\Xi^-\pi^0)$	148

Organizing the Data









1964: Quarks?

- Murray Gell-Mann:

Physical meson states are representations of the SU(3) symmetry group:

$$3 \otimes \overline{3} = 8 \oplus 1$$

Physical baryon states are representations of the SU(3) symmetry group:

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

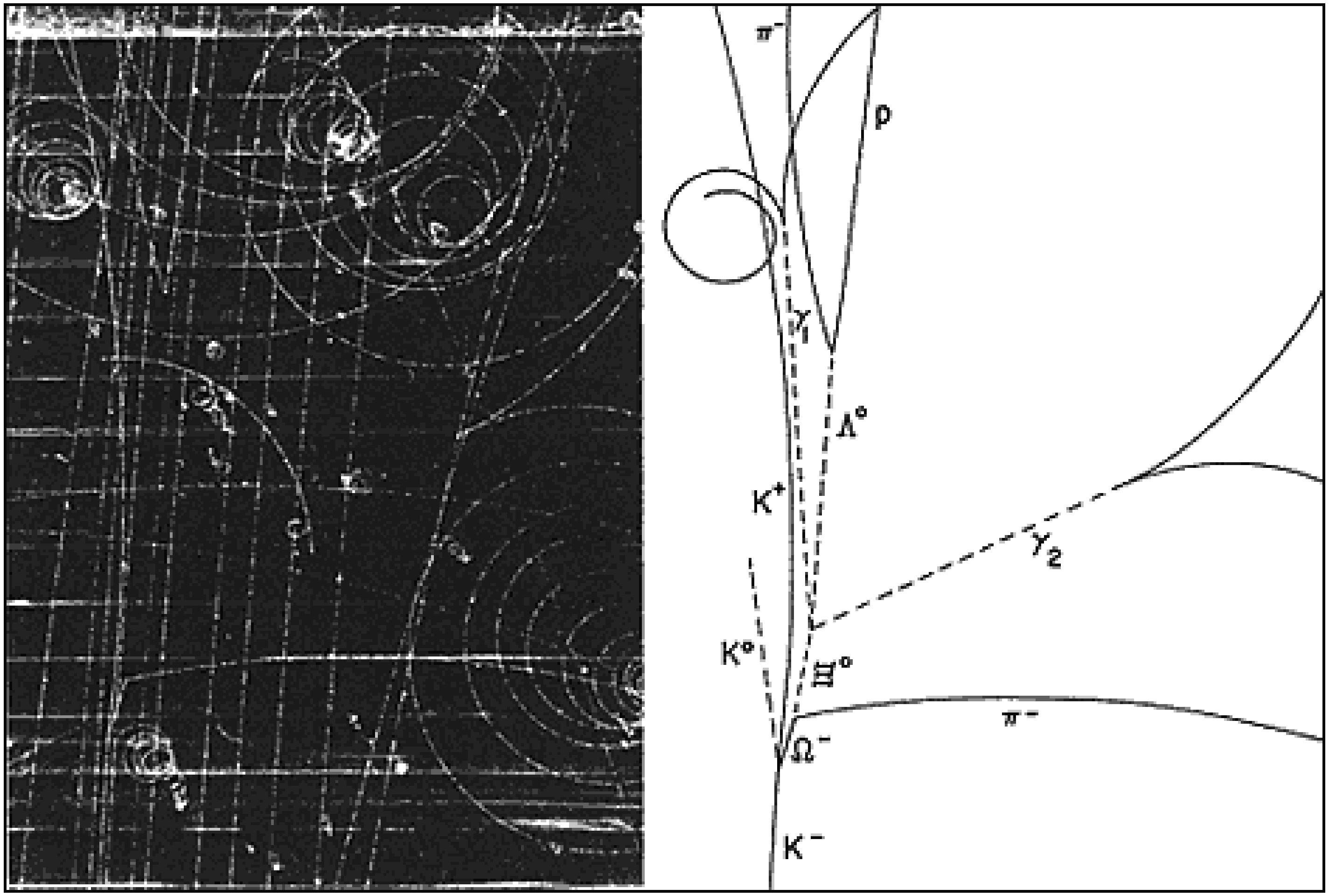
- George Zweig:

Hadrons are composed of more elementary objects:

$$\begin{aligned} \pi^+ &= (u\bar{d}) \\ \pi^- &= (\bar{u}d) \\ K^+ &= (u\bar{s}) \\ K^0 &= (d\bar{s}) \\ p &= (uud) \\ n &= (udd) \\ \Lambda &= (uds) \\ &\dots \\ \Omega^- &= (sss)? \end{aligned}$$

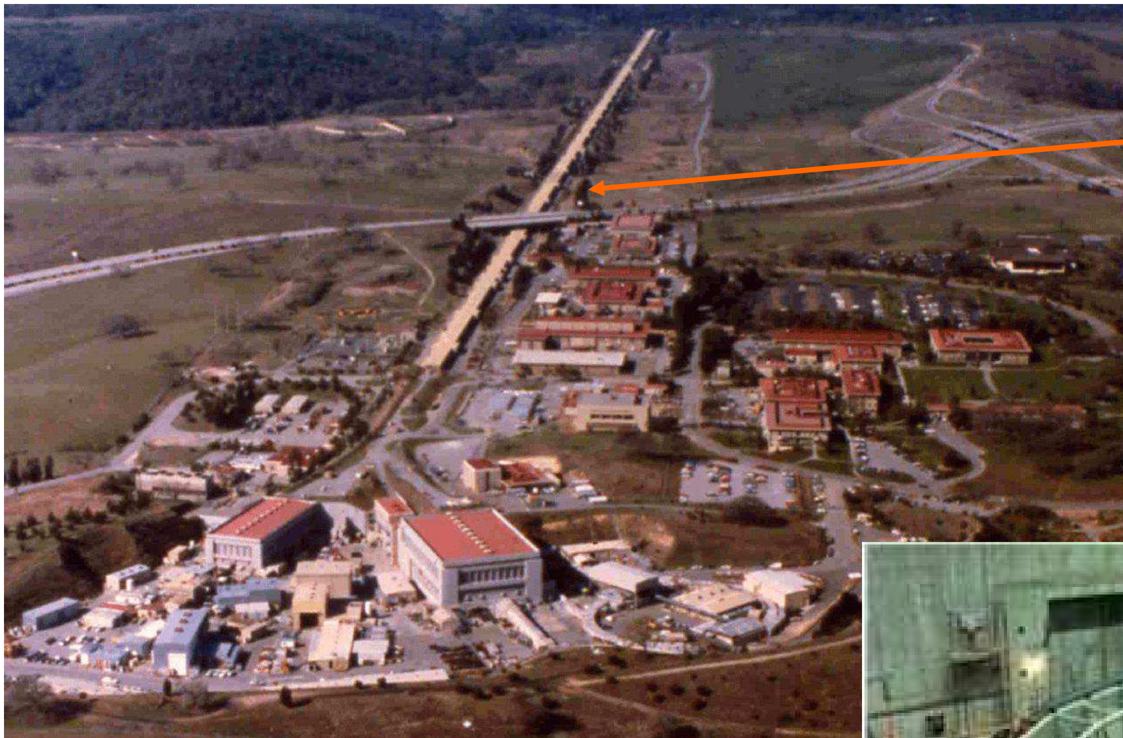
quark	charge	spin	strangeness
u	+2/3	1/2	0
d	-1/3	1/2	0
s	-1/3	1/2	-1

1964: Observation of the Ω^-

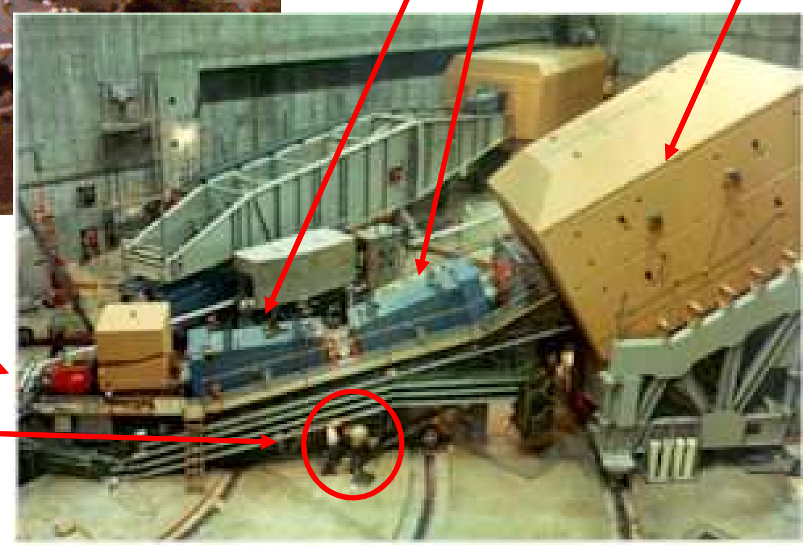


Observed in the 80 inch bubble chamber at Brookhaven in 1964.

1968: Deep Inelastic Scattering



2 mile long, 30 GeV electron accelerator



Analyzing magnets

Detector

Hydrogen target

People

Elastic Scattering

Used to measure the size of the proton.

$$r \sim 10^{-15}\ \text{m}$$

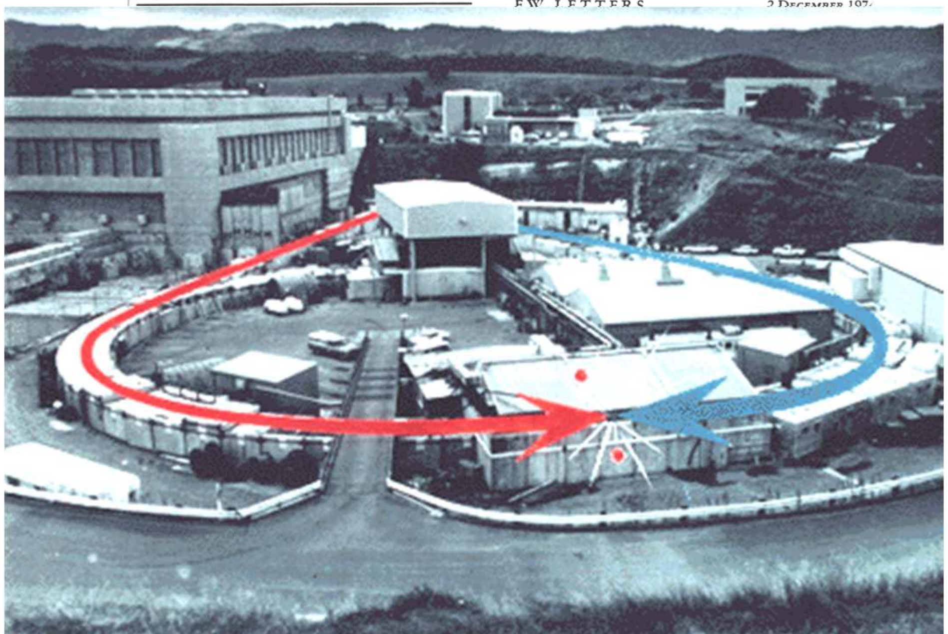
Inelastic Scattering

Deep Inelastic Scattering

Angular distribution consistent with
scattering from point-like spin ½ particles
inside the proton

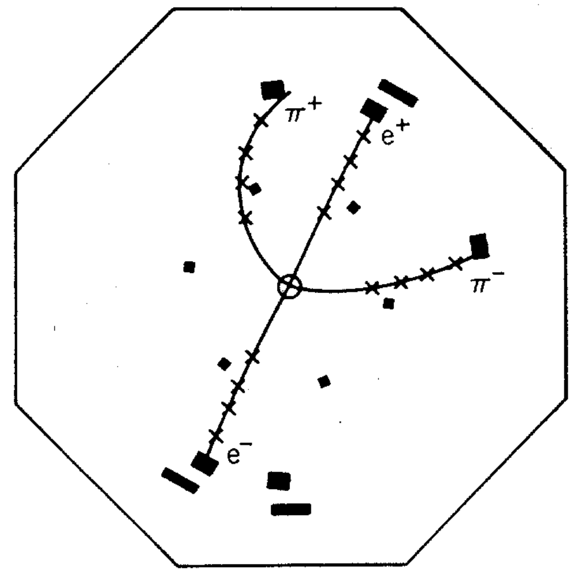
Exactly the same as the Rutherford scattering experiment

1974: The November Revolution



The SPEAR synchrotron: 8 GeV electron-positron collider at SLAC

Simultaneously observed at Brookhaven where it was called the "J".



$$\psi = (c\bar{c})$$
$$\psi' \to \psi\pi^+\pi^-$$
$$\psi \to e^+e^-$$

To this day it is called the J/ψ...

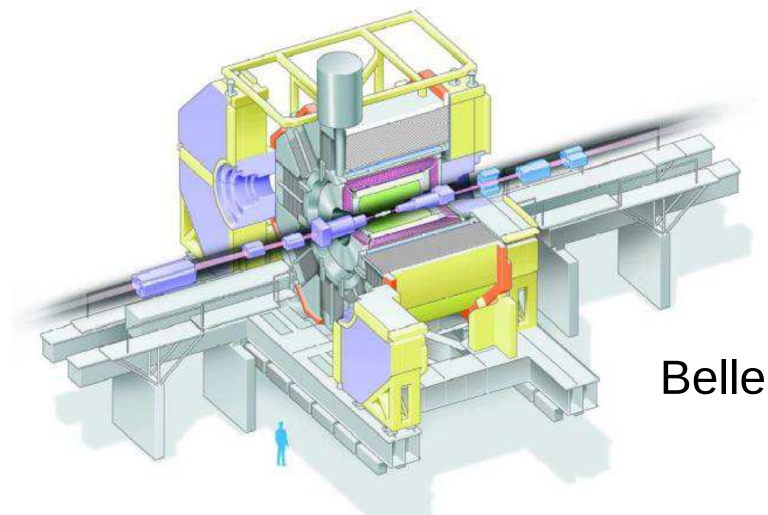
The Mark-I detector tracked charged particles using spark chambers

The charm quark was heavy and non-relativistic.

Charmonium behaved like a hydrogen atom made of quarks.

Bottom Quarks

- Discovered in 1977 at a 400 GeV fixed target experiment, Fermilab E-288.
- Studied in detail with the ARGUS detector at Hamburg and CLEO at Cornell in the 80's and 90's.
- B-factories now operate at SLAC (BaBar) and in Japan (Belle)
- Detailed studies of how the weak force interacts with quarks.



Belle

Fundamental Particles of Matter

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

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

- In 1994 the top quark was discovered by the CDF and DØ experiments at Fermilab
- In 2000 the tau neutrino was observed by the DONUT experiment at Fermilab
- The top quark is very heavy (174 GeV/c^2) and it decays directly via $t \to W^+ b$....

Returning to the 1950's: Quantum Electrodynamics

- A complete description of electrons, positrons and photons using relativistic quantum mechanics.
- In quantum mechanics, observable quantities are calculated using the "wavefunction" for a particle.
- The definition of the wavefunction is not unique... it could be arbitrarily re-defined at each point in space without changing any observables.
- This works, provided the electron interacts with the photon.

Symmetry $\Longrightarrow$ Forces

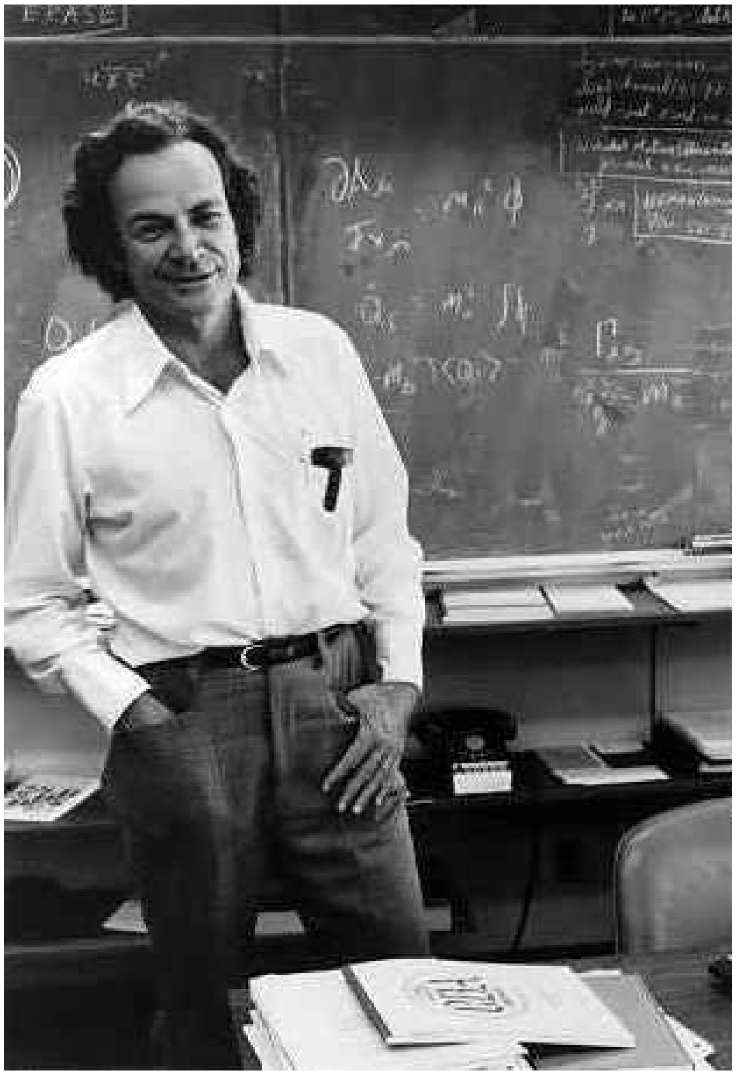
Quantum Electrodynamics

- Electron-electron scattering:

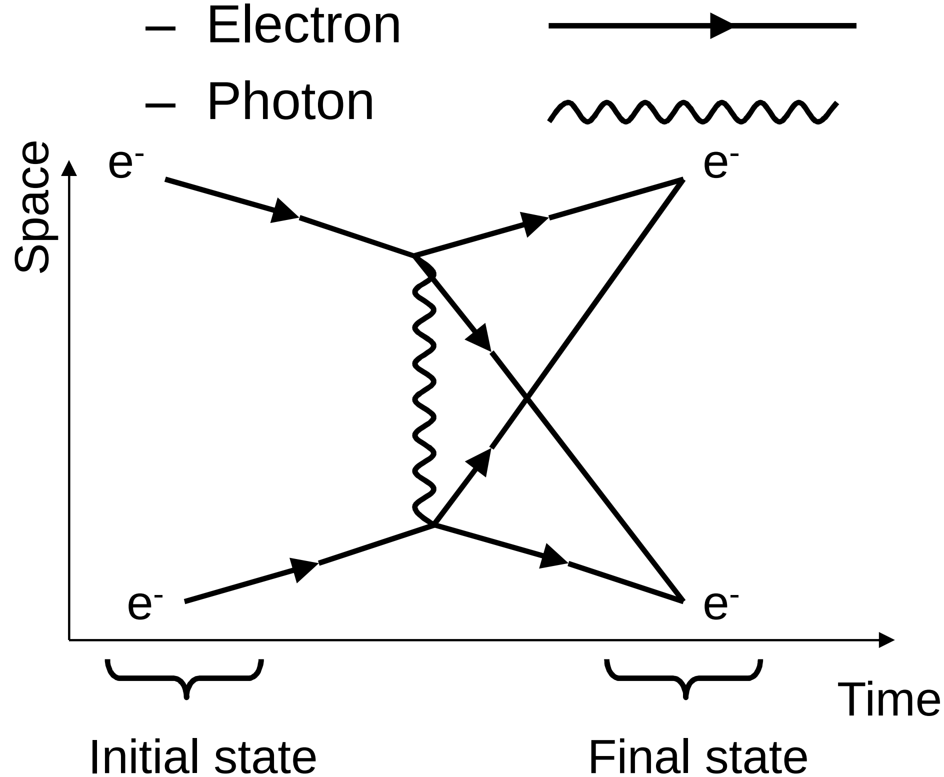
$$|\mathcal{T}|^2 =$$ [redacted]

CENSORED

Quantum Electrodynamics



- Feynman Rules:
  - Electron
  - Photon

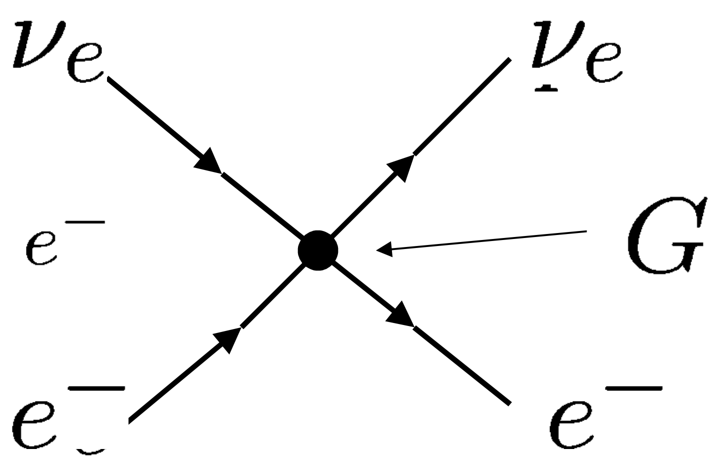


  - Add together ALL possible Feynman diagrams

Weak Interactions

- Beta decay described by Fermi (1930's):

$$\nu_e + e^- \to \nu_e + e^-$$

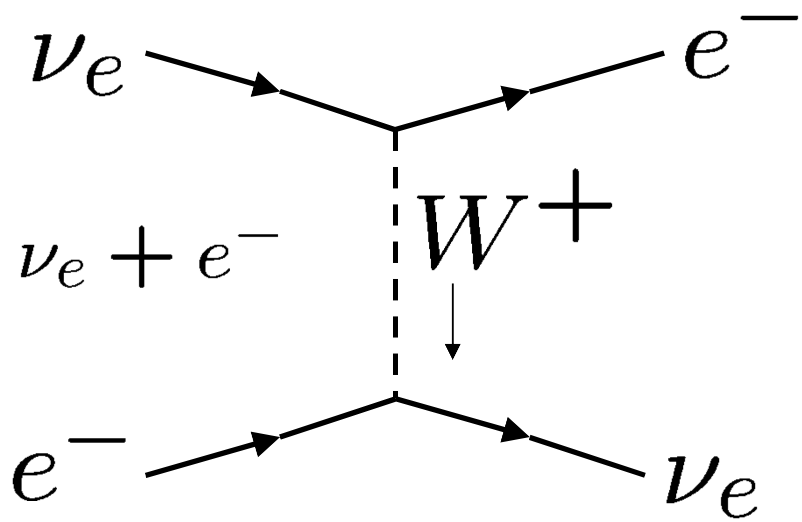


- Predicted that the probability of elastic neutrino scattering would exceed unity at energies of around 100 GeV.

Weak Interactions

- A significant improvement:

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

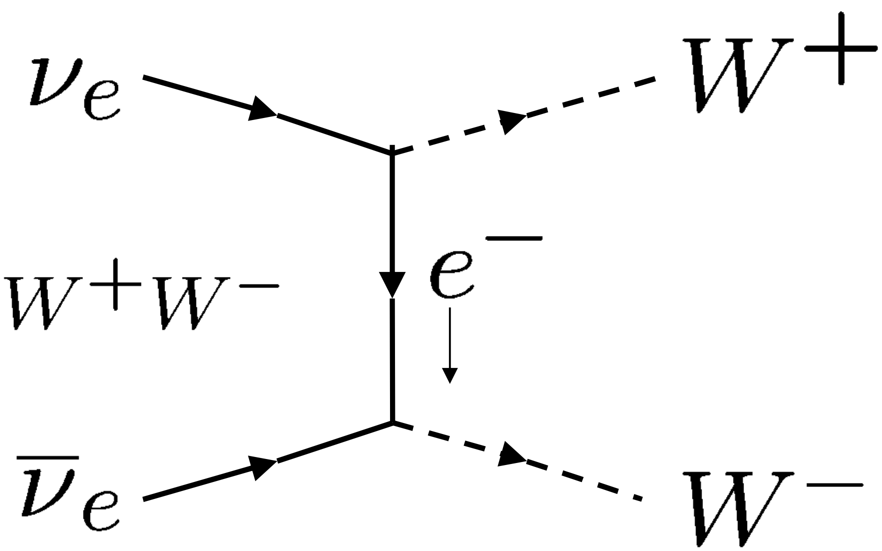


- A very massive W boson would explain why the interaction is weak.

Weak Interactions

- But hypothetically, at least:

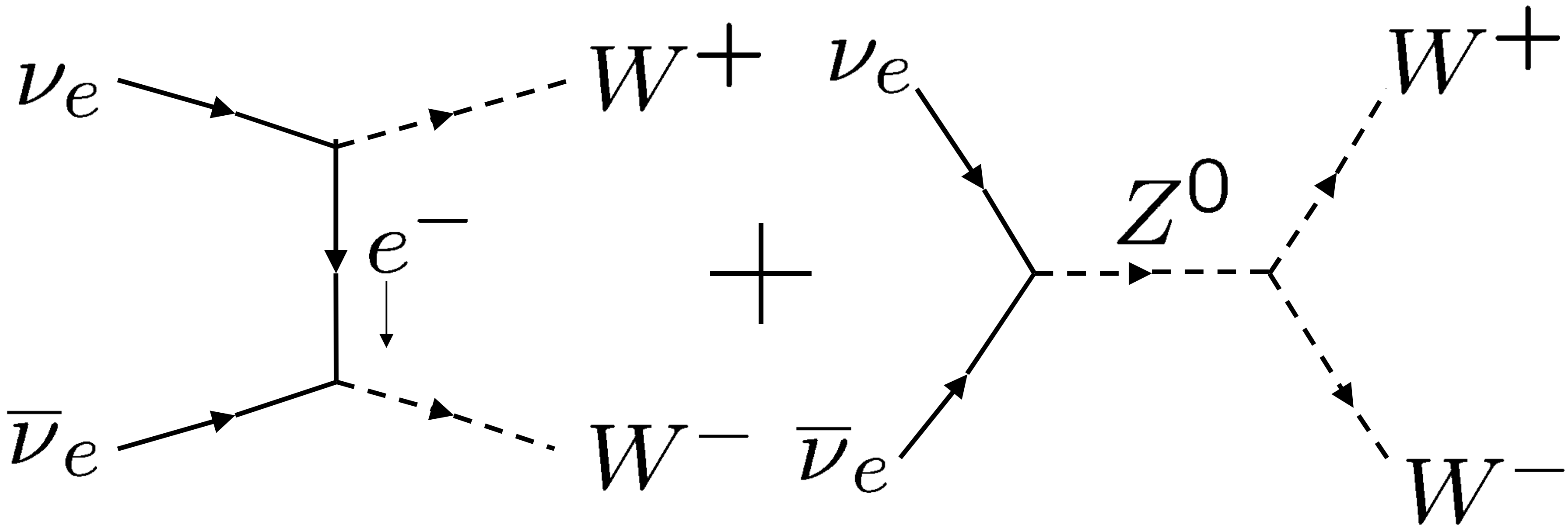
$$\nu_e + \overline{\nu}_e \rightarrow W^+W^-$$



- At high energies, the probability for W^+W^- production by “neutrino-neutrino” scattering would exceed unity.

Weak Interactions

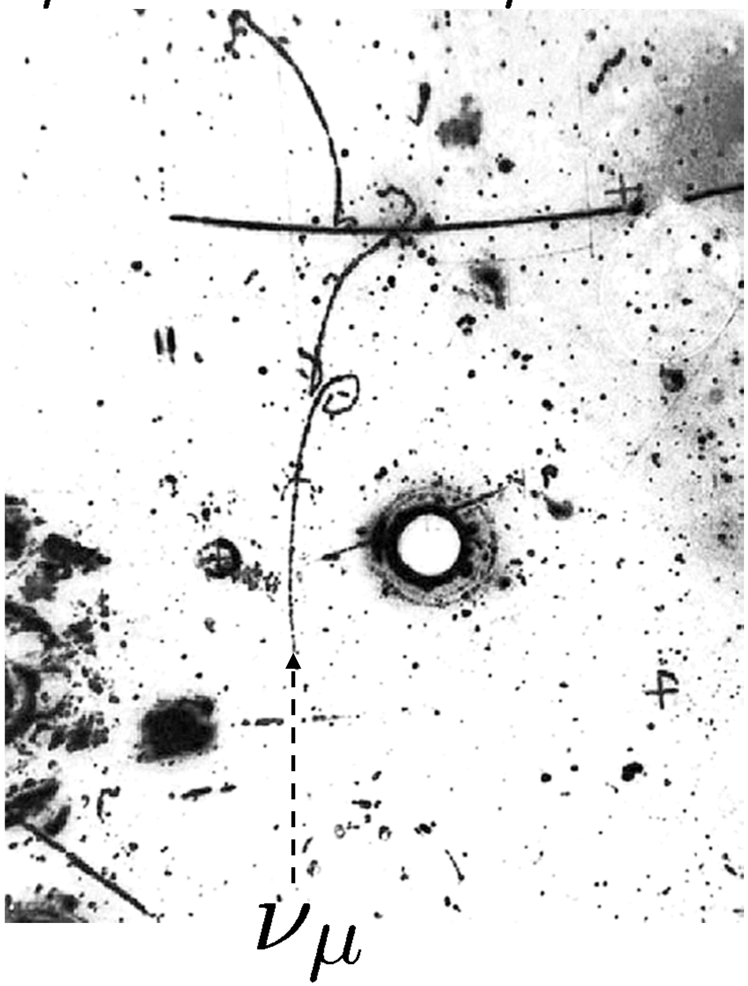
- This combination worked:



- But it required adding a new, neutral boson to the theory.

Observation of Neutral Currents

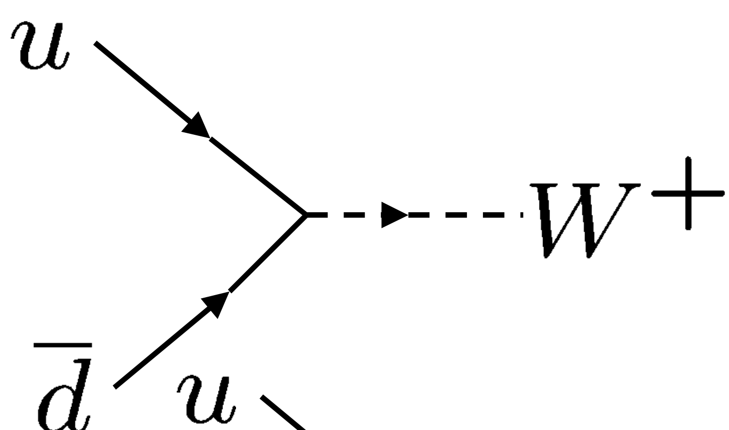
$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$

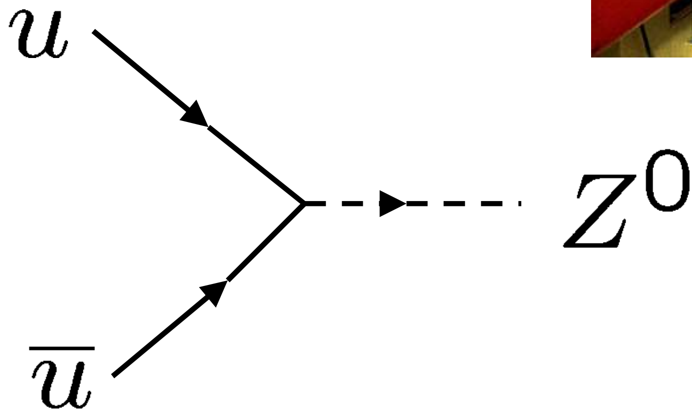


- Observed in 1973 at CERN in a liquid freon bubble chamber.
- Masses of the $W^\pm$ and Z^0 predicted to be of order 100 GeV/c^2

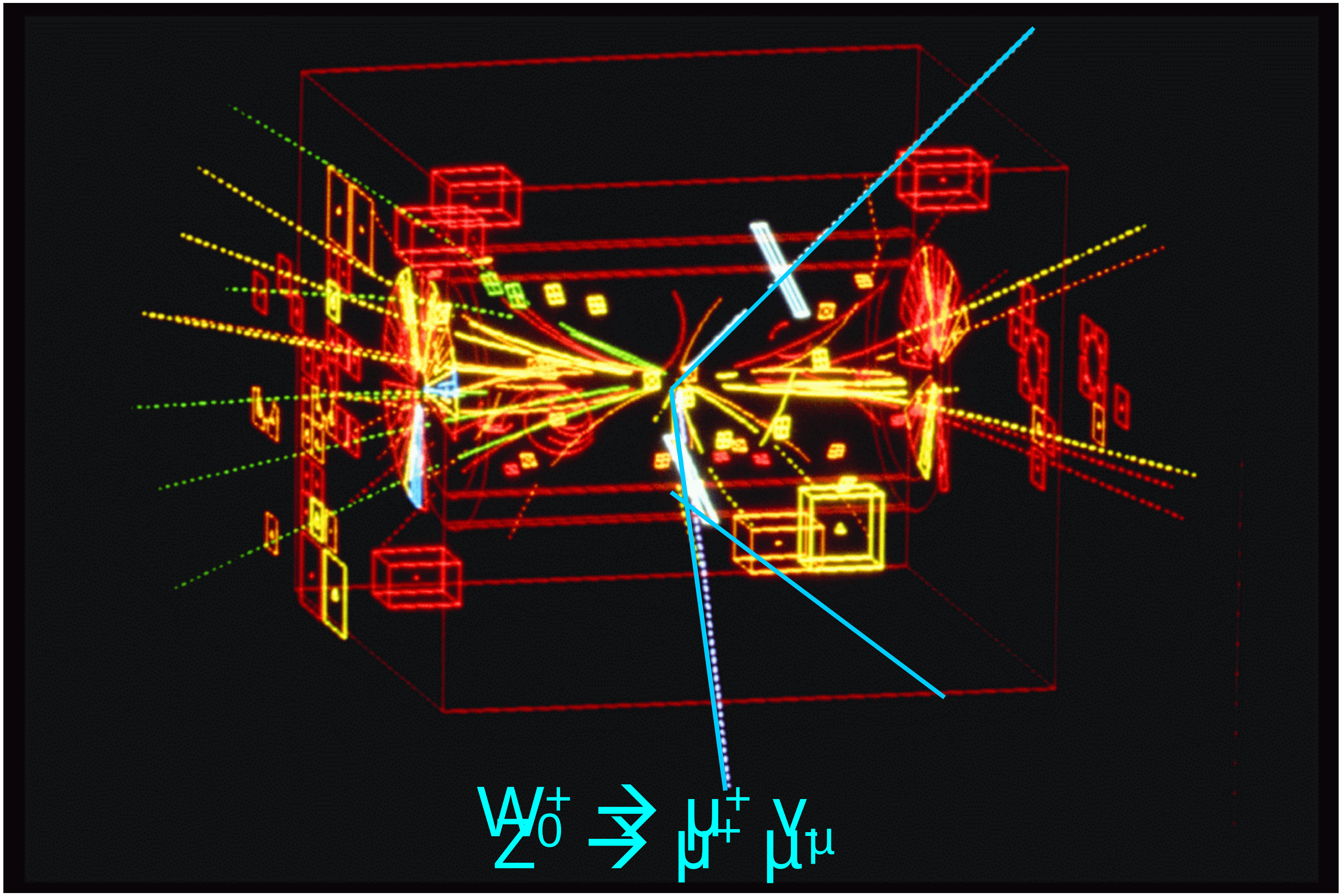
The CERN SPS

- Produce $W^{\pm}$ and Z^0 directly by colliding quarks and anti-quarks:





1983: Observation of W and Z Bosons



But there's more...

- A theory with explicit mass for W's and Z's is "Non-renormalizable" – $\mathcal{P} \longrightarrow \infty$
- A theory with massless W's and Z's is renormalizable...
- By introducing the Higgs mechanism we get the best of both worlds.
- But we've added a new particle to the theory... one that hasn't yet been observed.

The Standard Model

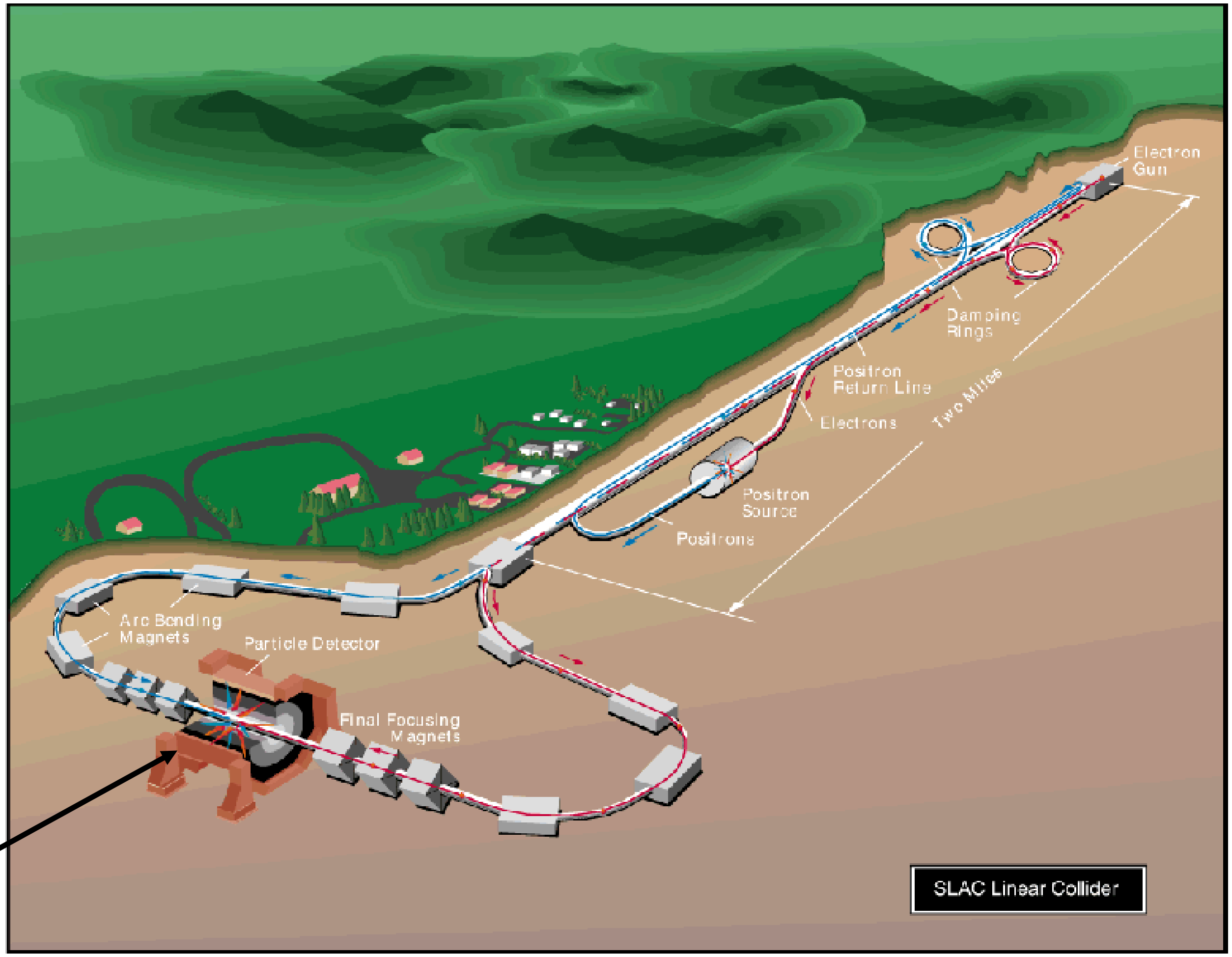
Charge				
+2/3 −1/3	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$\begin{pmatrix} c \\ s \end{pmatrix}_L$	$\begin{pmatrix} t \\ b \end{pmatrix}_L$	Quarks
+2/3 −1/3	$(u)_R$ $(d)_R$	$(c)_R$ $(s)_R$	$(t)_R$ $(b)_R$	
0 −1	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	Leptons
−1	$(e)_R$	$(\mu)_R$	$(\tau)_R$	
	W^+, W^-, Z^0, γ 8 gluons			Gauge bosons
	H^0			Higgs boson

SLAC and LEP

- Masses of the $W^{\pm}$ and Z^0 were known
- Build electron-positron colliders to produce them in large numbers
- Make precision measurements tests of the Standard Model

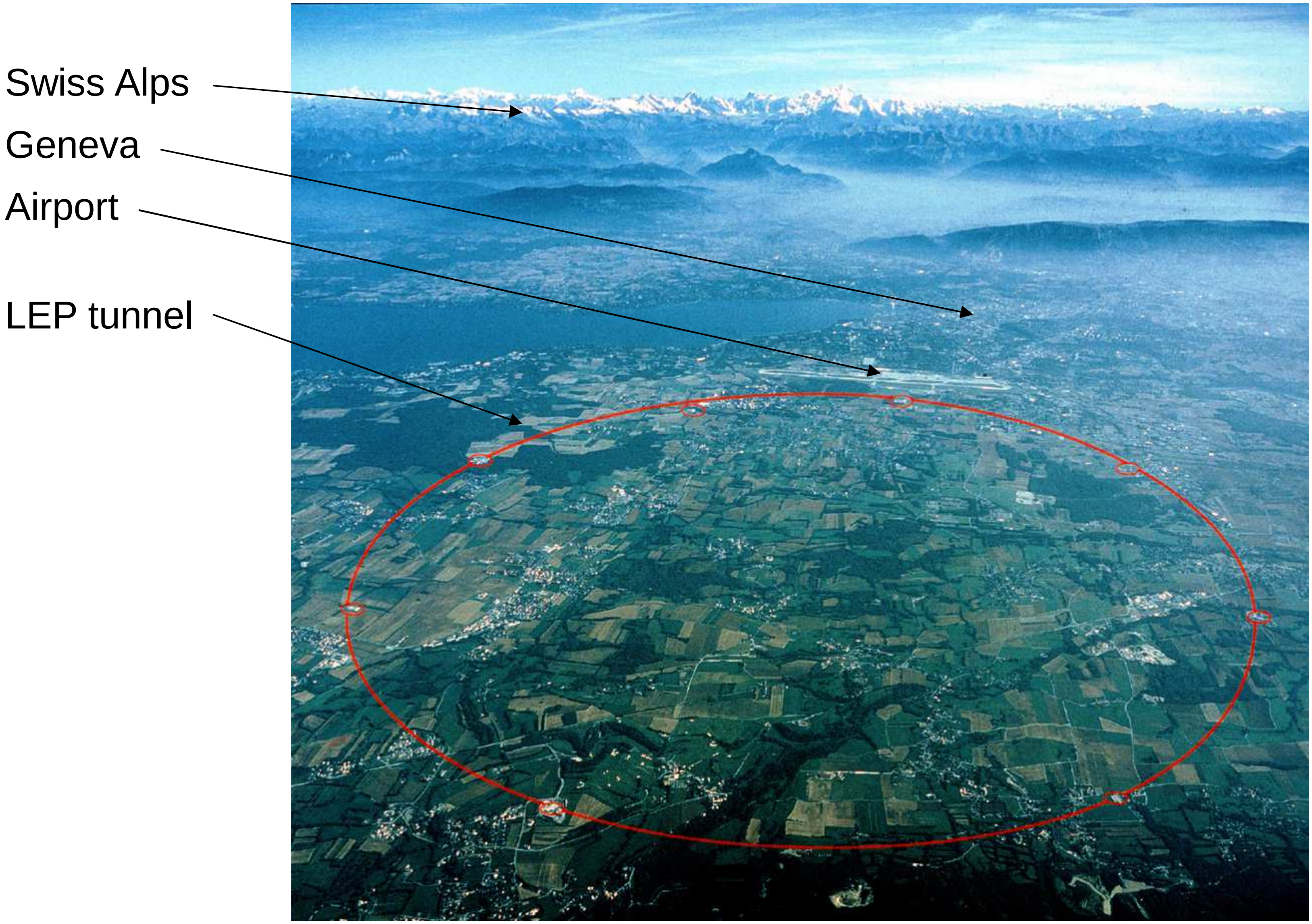
- SLAC upgraded their linear accelerator...
- CERN dug a BIG tunnel...

1987: Stanford Linear Collider

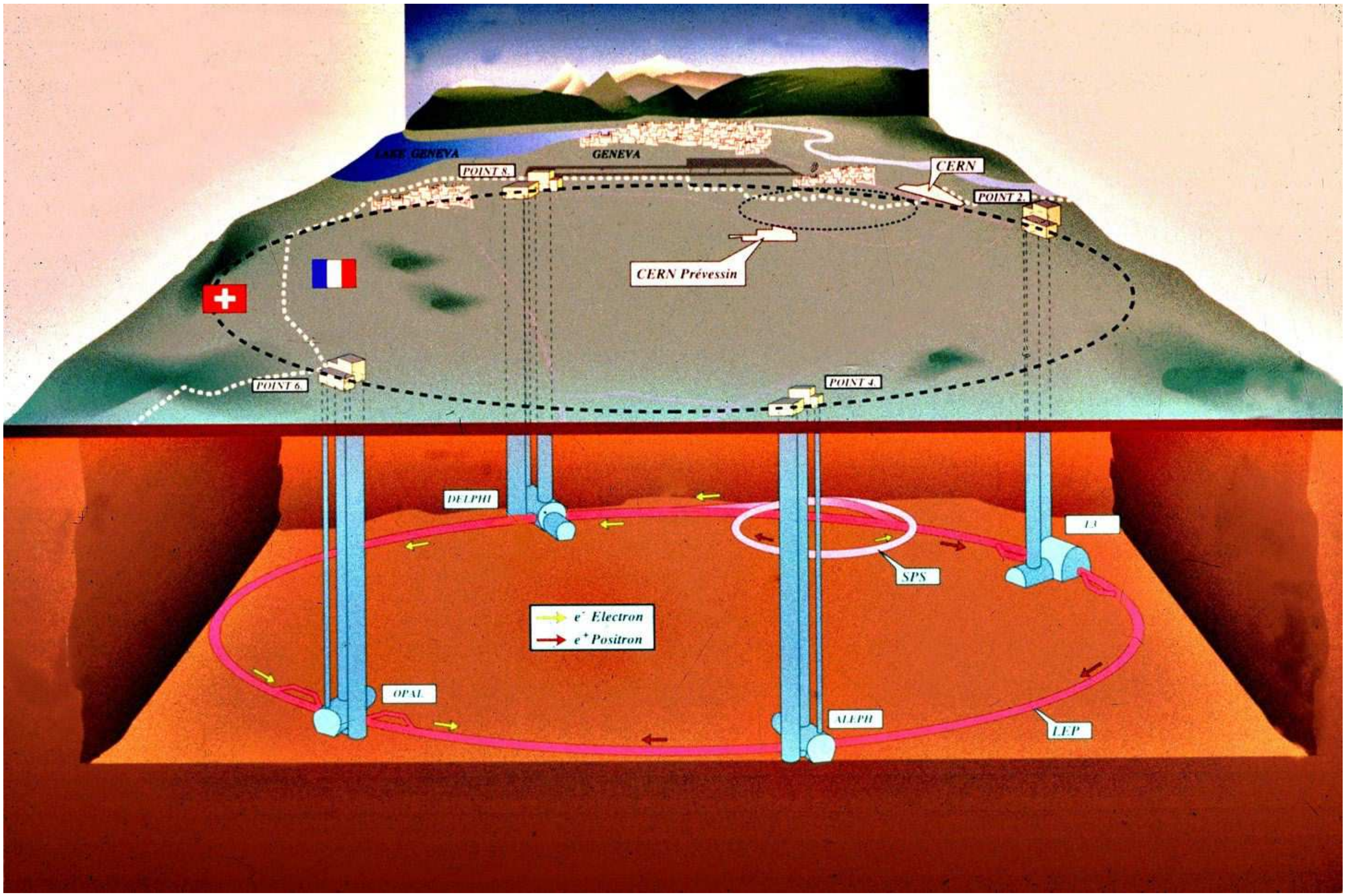


SLD detector

Large Electron Positron Collider

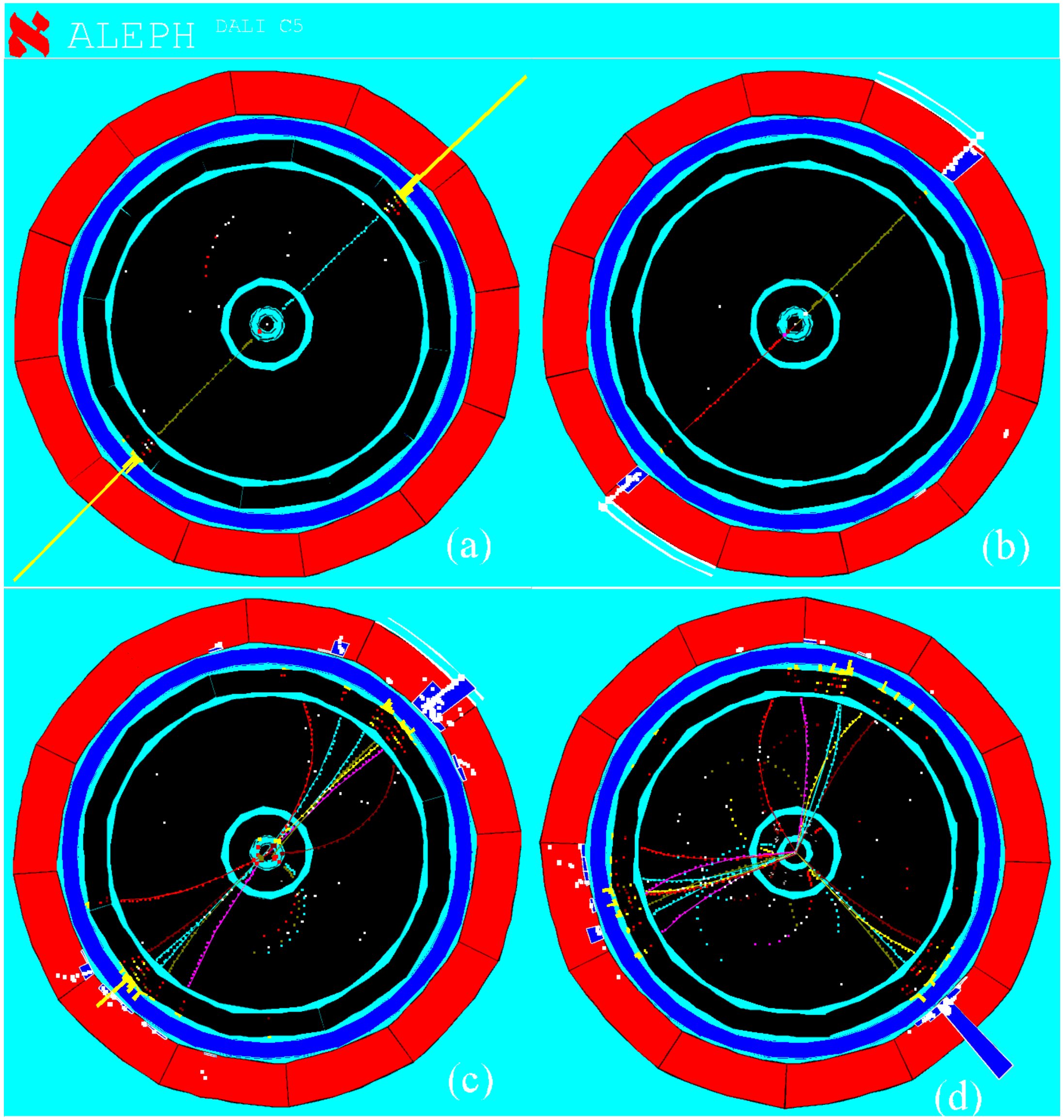


ALPEH, DELPHI, L3, OPAL

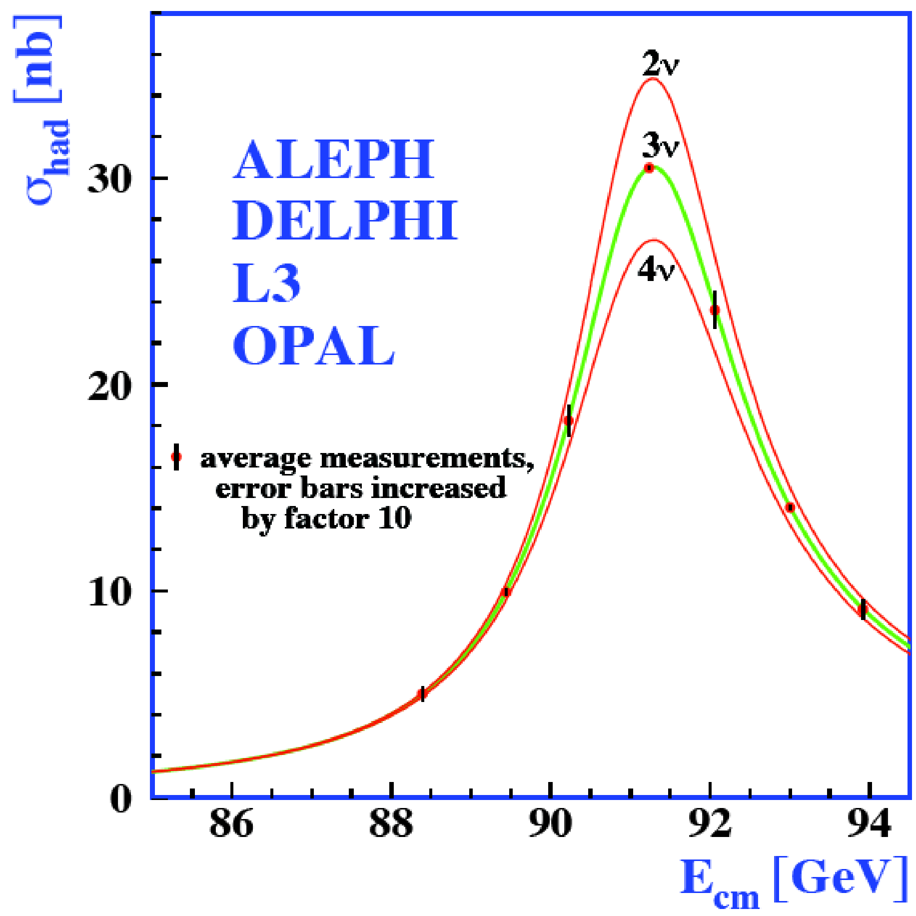


Z^0 Production at LEP

$$
\begin{aligned}
Z^0 &\rightarrow e^+e^- \\
&\rightarrow \mu^+\mu^- \\
&\rightarrow q\bar{q} \\
&\rightarrow q\bar{q}g \\
&\dots
\end{aligned}
$$



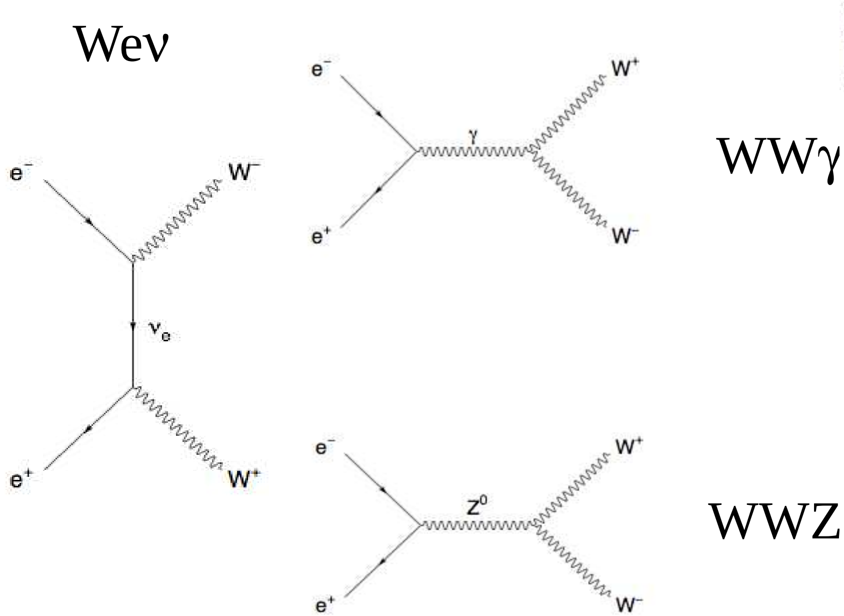
Physics from LEP

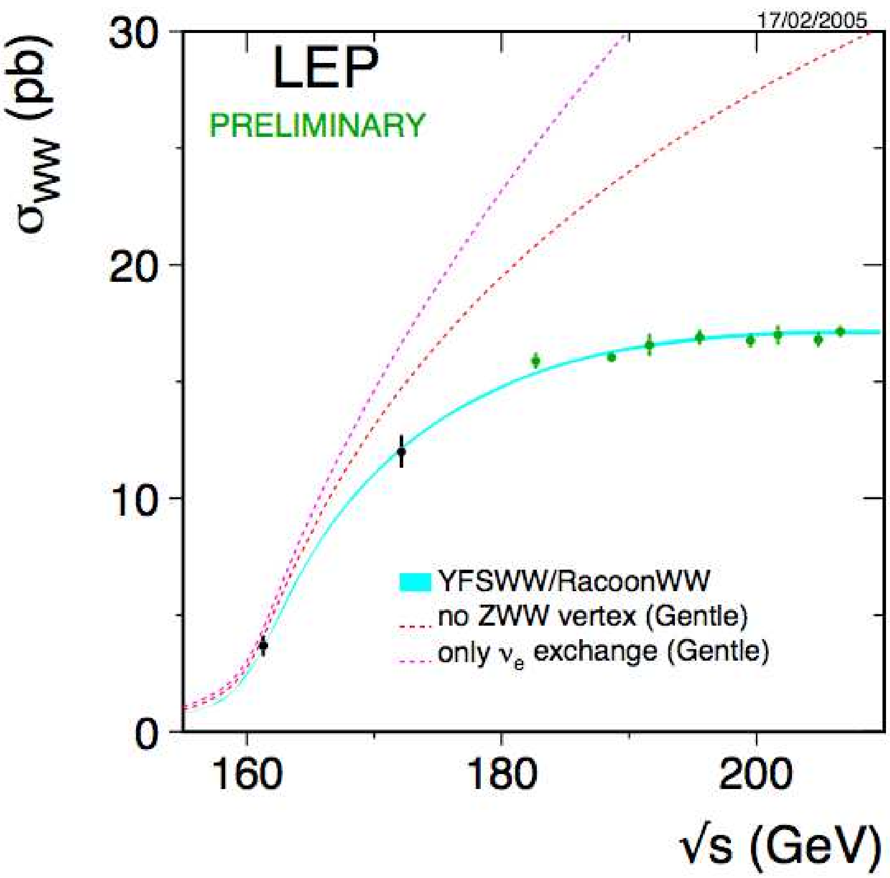


$N_\nu = 2.9841 \pm 0.0083$

- Only 3 generations of quarks and leptons.

1997: LEP II – W^+W^- Production





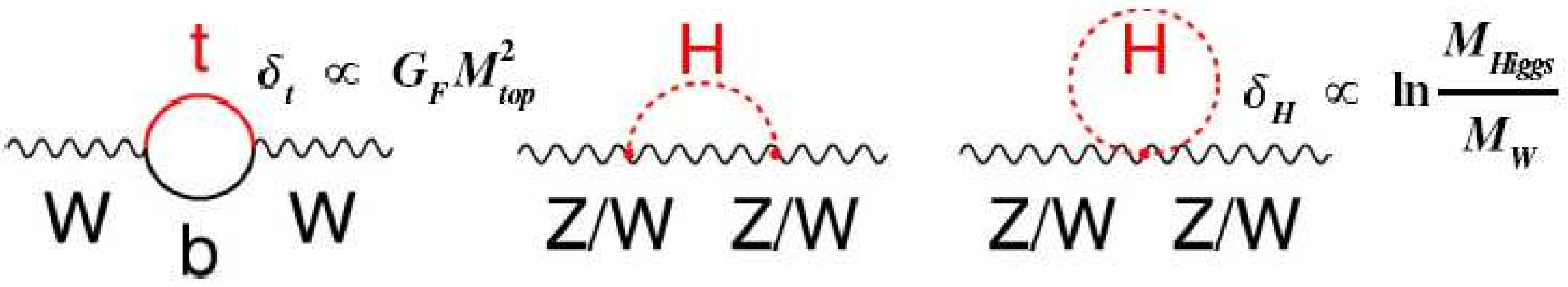
All Feynman diagrams are needed to explain the observed W^+W^- production cross section.

The Higgs Boson?

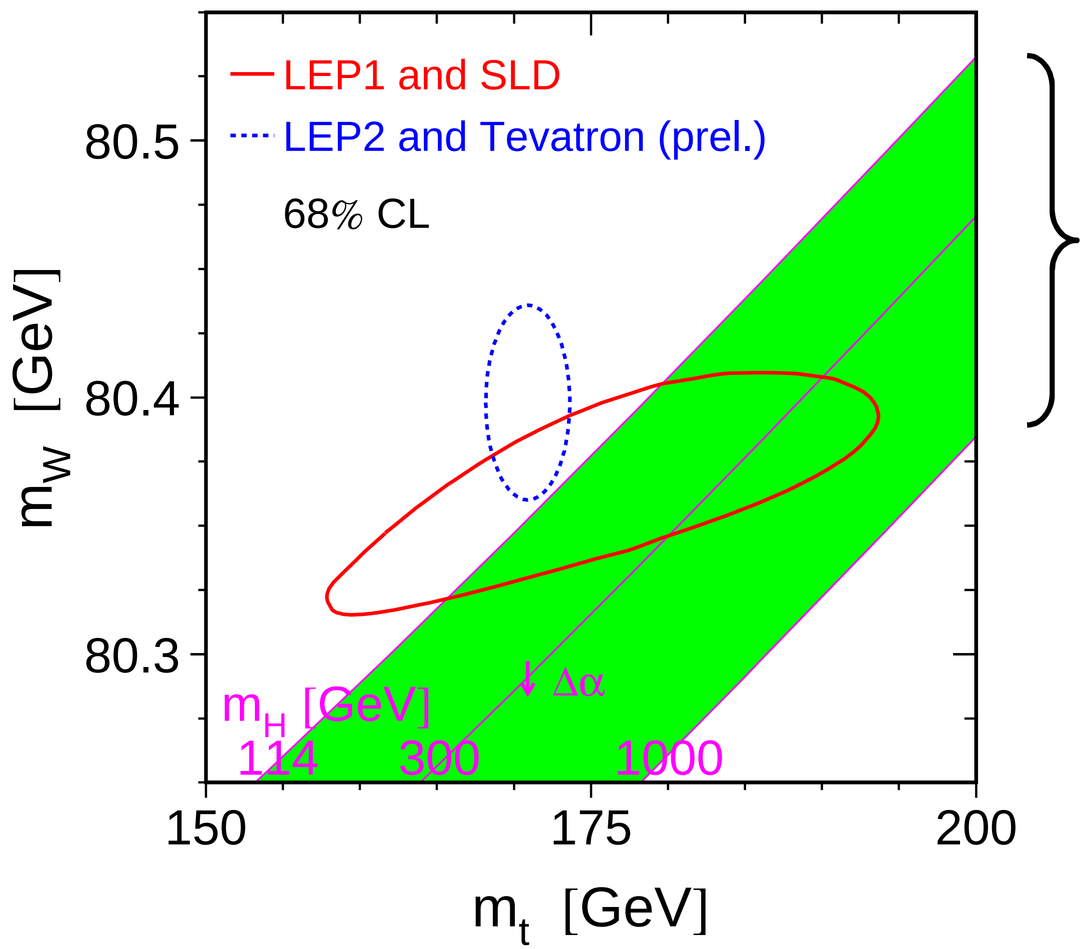
- Direct searches at LEP did not find it.

$$M_H > 114.4 \text{ GeV}/c^2$$

- Although not directly observed, it should influence precision measurements:



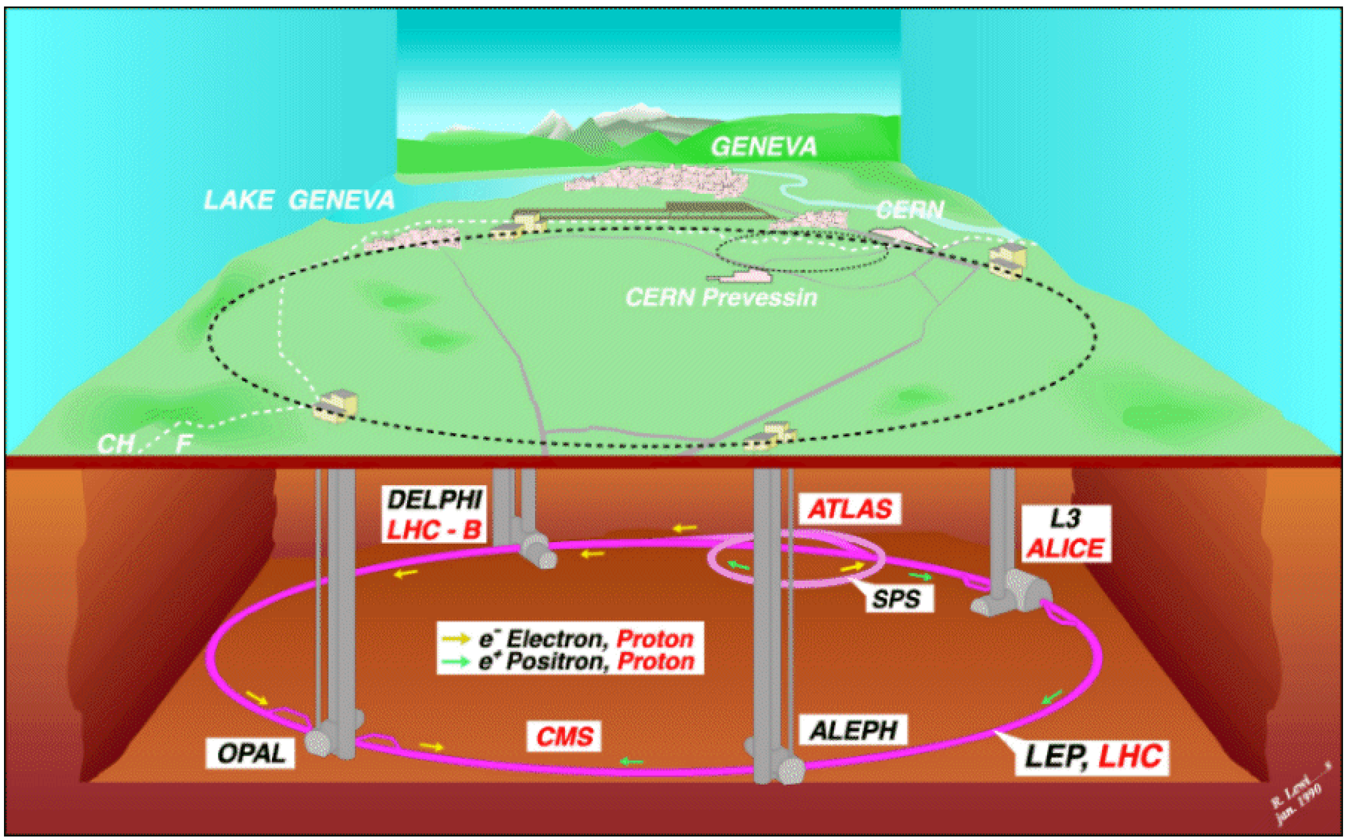
The Higgs Boson



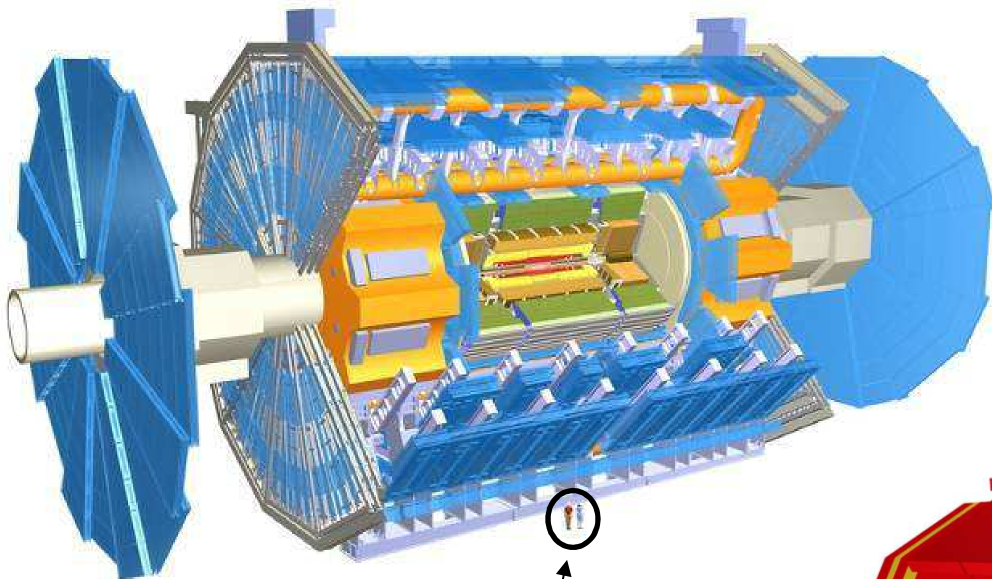
Could it be just around the corner?

The Large Hadron Collider

- Replaced LEP with a proton-proton collider
- Seven-fold increase in energy – 14 TeV

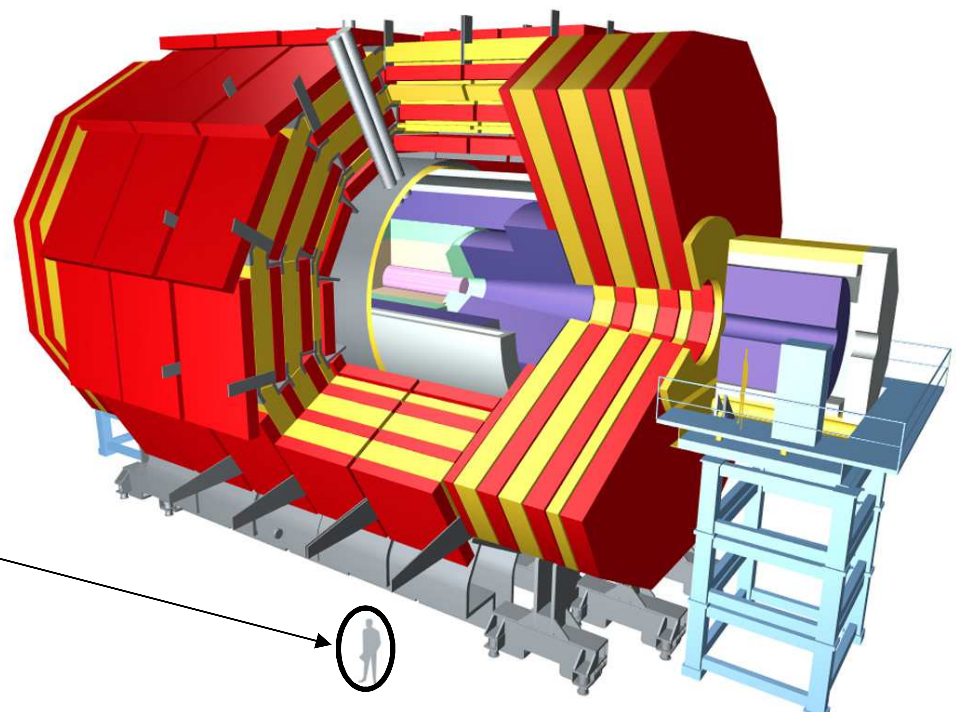


CMS and ATLAS



High energy collisions and high intensity beams require complex detectors.

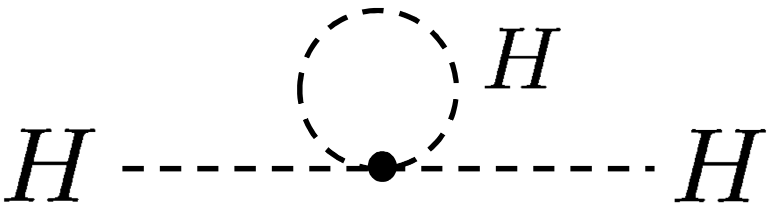
Lots of money, lots of people.



People

What we still don't understand

- Why is the Higgs mass finite?



- Supersymmetry would fix this problem but would introduce *hundreds* of new particles.
- Neutrinos have mass! That breaks the standard model.
- Why are there only three generations of quarks and leptons?
- Are there only 4 space-time dimensions?
- No easy way to incorporate gravity...

Conclusions

- Matter is composed of fundamental, elementary particles.
- We can describe their properties with exquisite precision using Quantum Field Theory.
- We know our knowledge is incomplete.
- We hope that the LHC will give us new (and badly needed) experimental results.