Elementary Particles

and

Interactions

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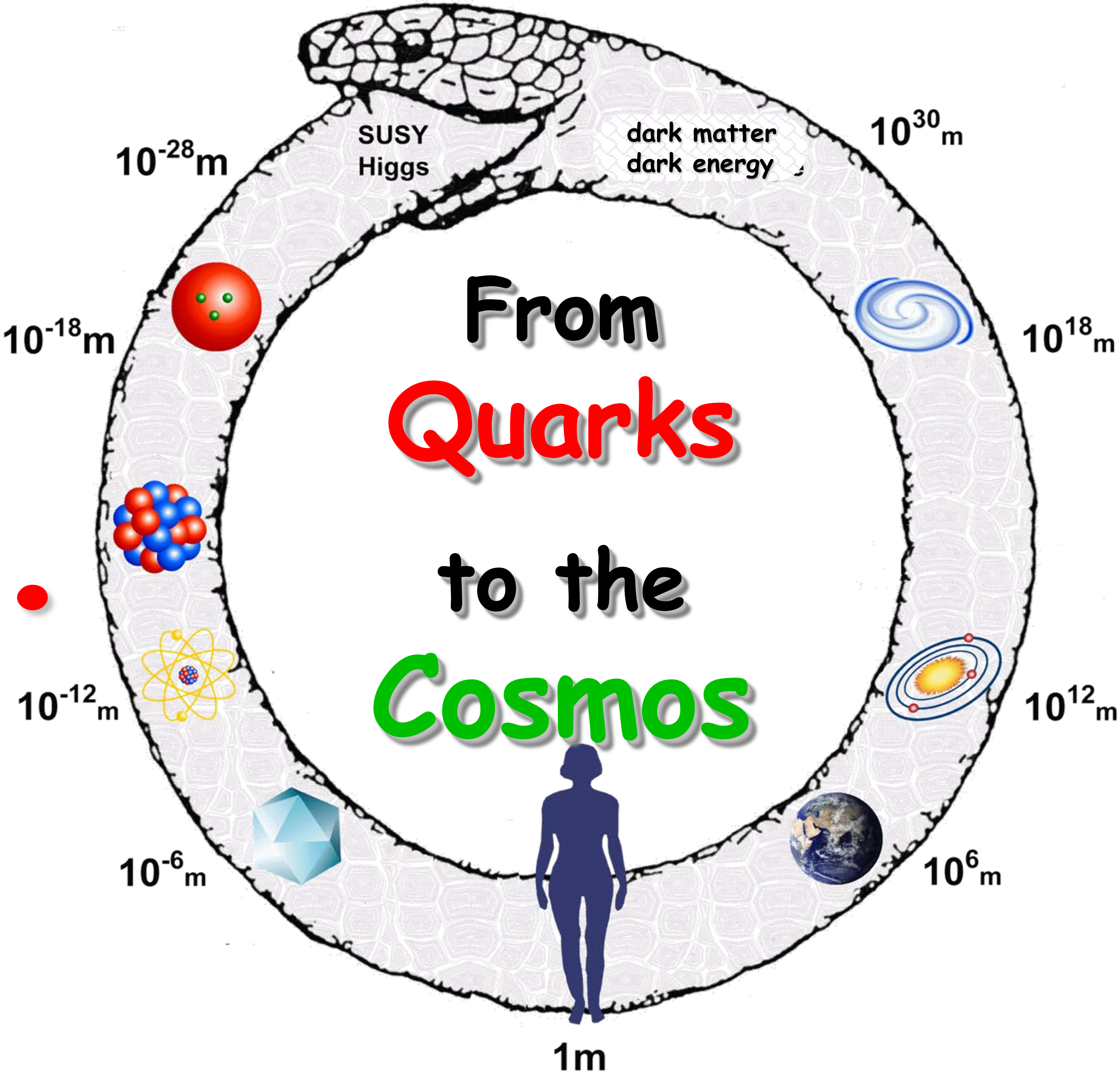
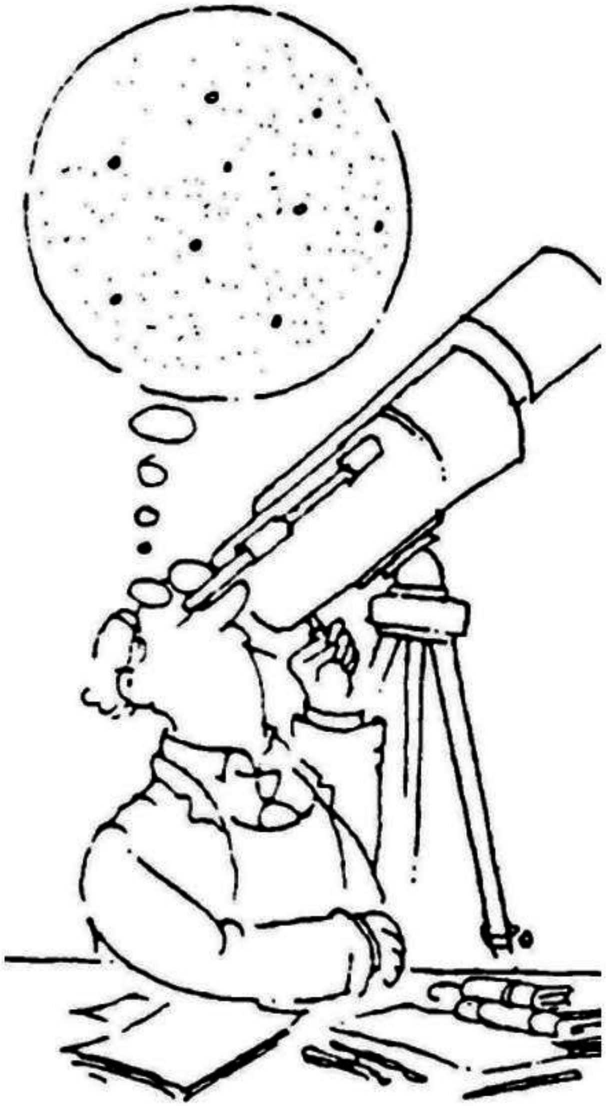
1. From Quarks to the Cosmos

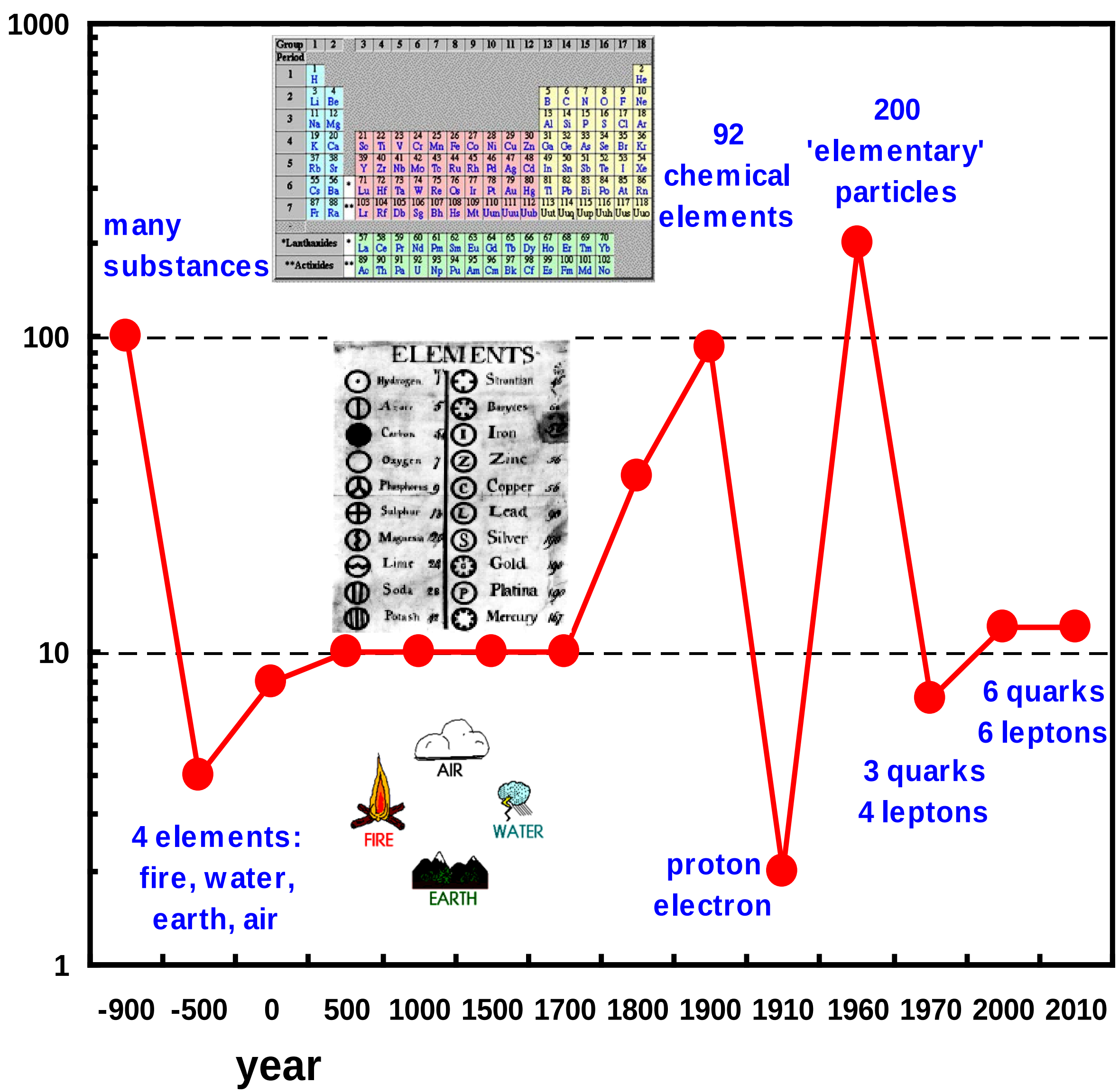


Microcosm - Macrocosm



The Building Blocks

The Building Blocks of Matter

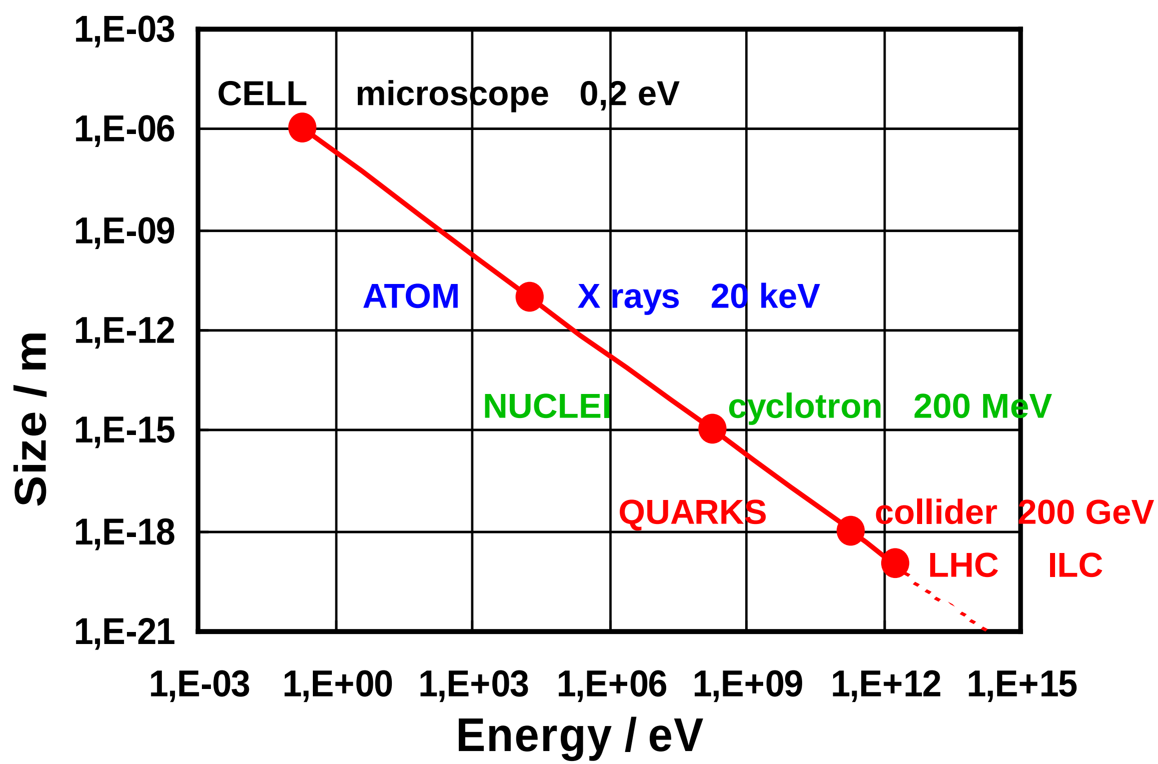


Structure of Matter

subatomic units:
electron-volt

Energy	Size	Device	Object	Year
0.2 eV	10^{-6} m	microscope	cell	1600
20 keV	10^{-11} m	X rays	atom	1910
200 MeV	10^{-15} m	cyclotron	nuclei	1946
200 GeV	10^{-18} m	collider	quarks	1998

uncertainty relation



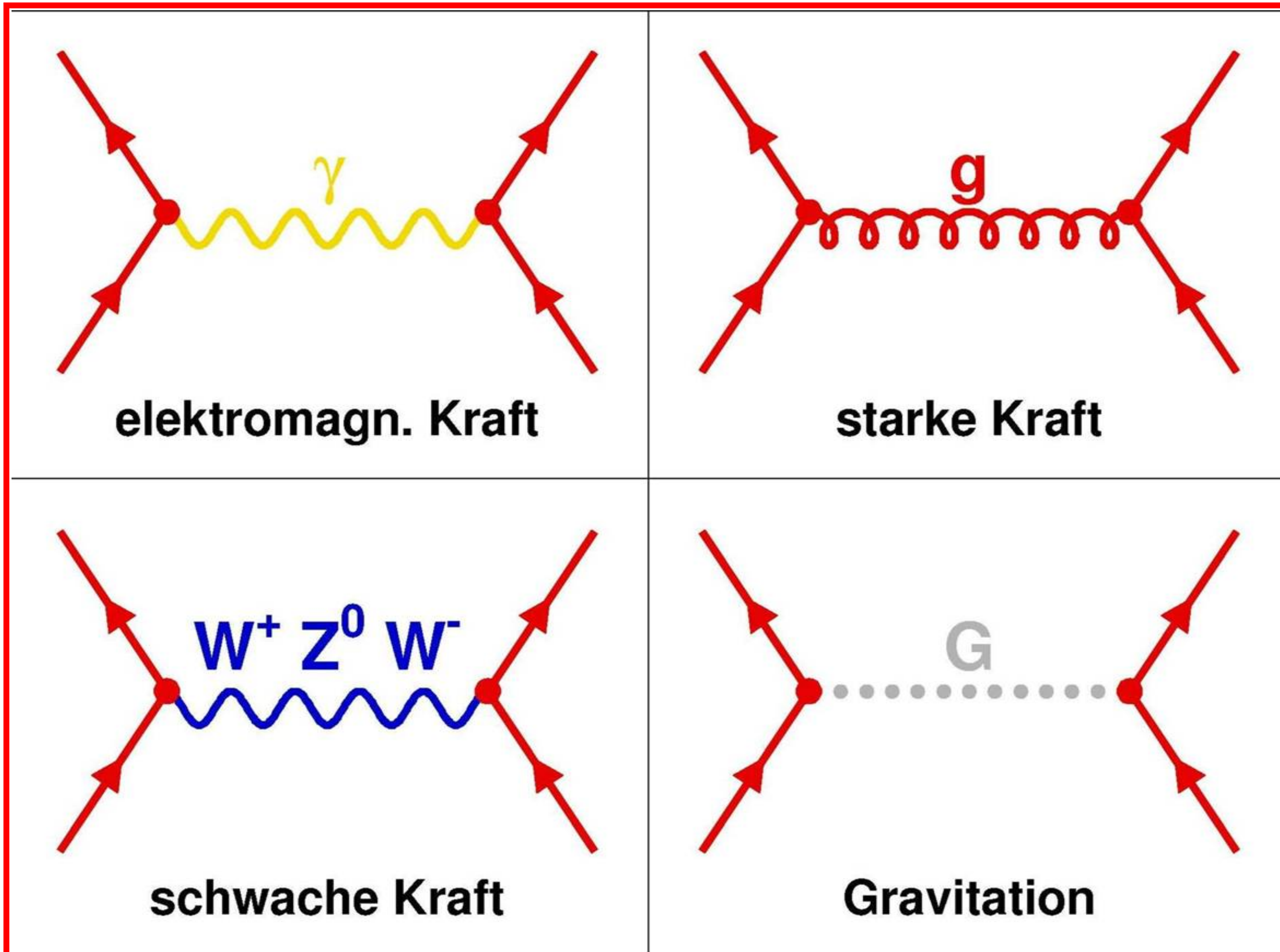
$1\ eV = k \cdot 11\ 604\ K$

$\Delta p\ \Delta x = \hbar$

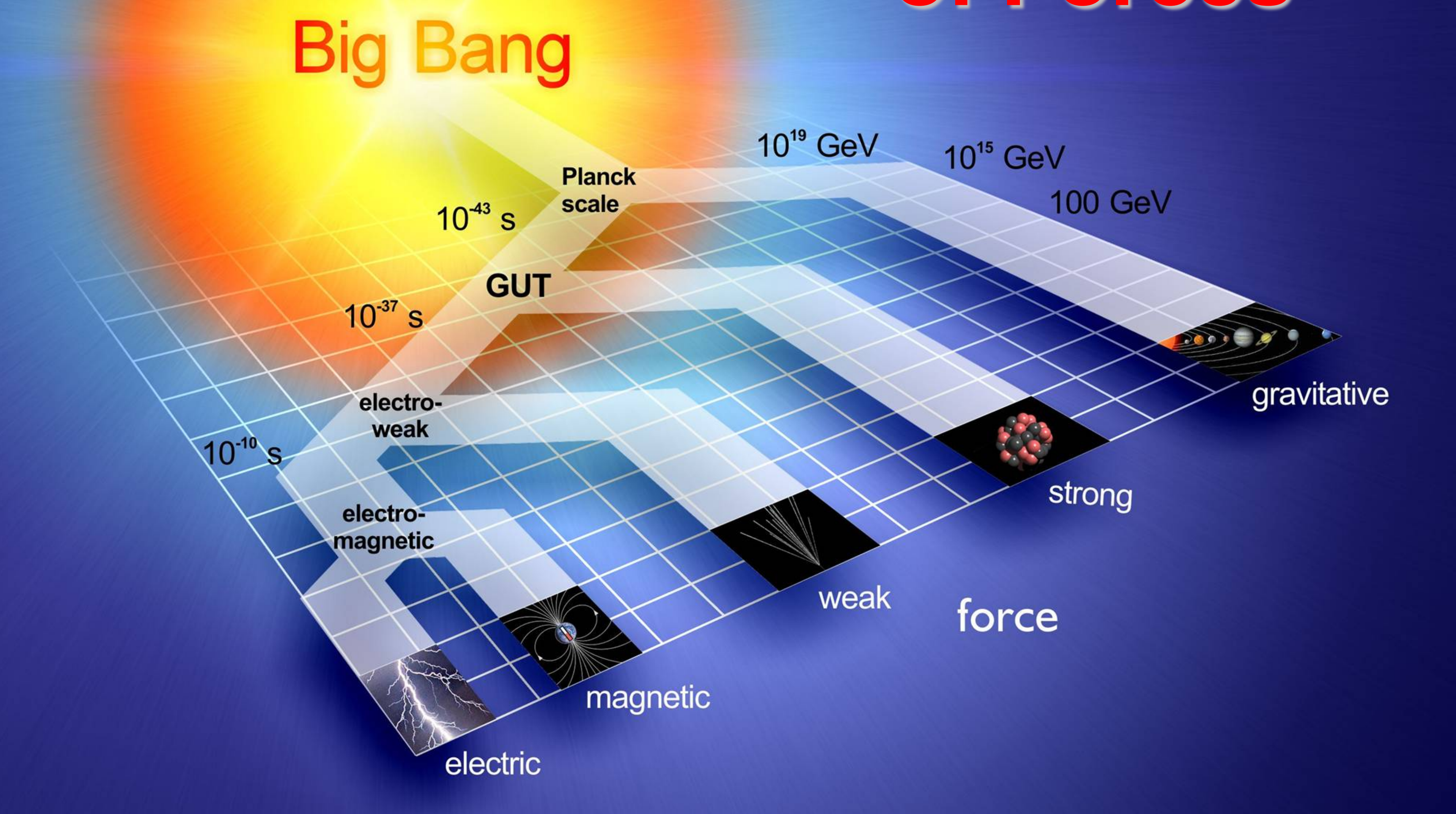
$\approx$

200 MeV/c fm

The Forces


γ
elektromagn. Kraft
g
starke Kraft
W+ Z0 W-
schwache Kraft
G
Gravitation

Unification of Forces



The Positron

- **curvature** R in magnetic field B: $R \sim p \sim 1/B$
- **ionization** I ~ velocity $\beta = v/c$: $I \sim 1/\beta \sim 1/(p/m)$

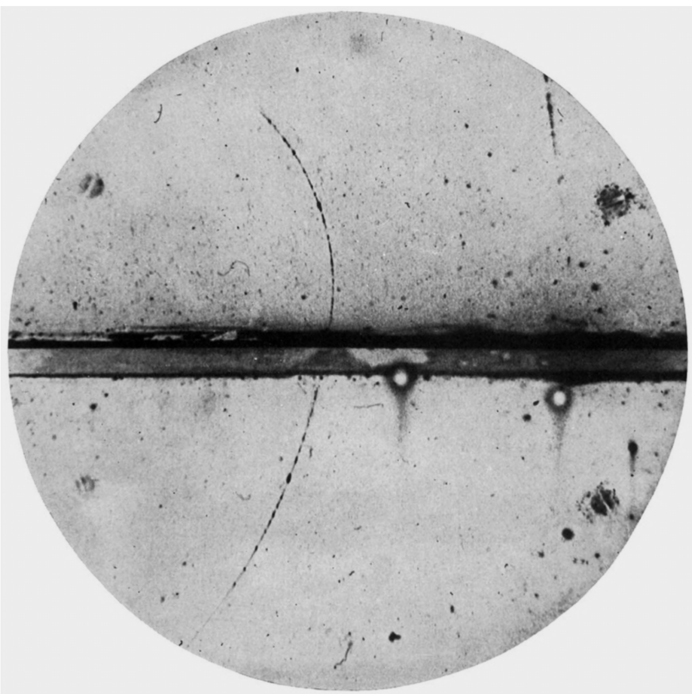


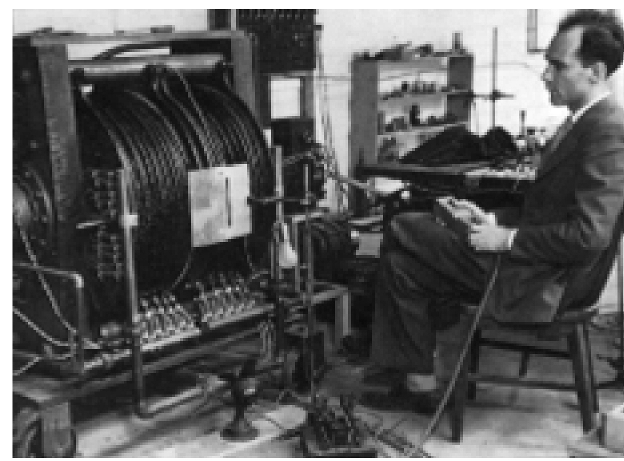
FIG. 1. A 63 million volt positron ($H\rho = 2.1\times10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5\times10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

C. Anderson,

The Positive Electron

Phys.Rev. 43, 491 (1933)

Wilson's cloud chamber



Nobel prize 1936 C. Anderson for the discovery of the positron
Nobel prize 1927 Ch. Wilson for the cloud chamber

Antimatter

Dirac, 1928:

relativistic theory of electrons

The only equation in Westminster Abbey:

$$(i\hbar c \not{\partial} - mc^2)\psi = 0$$

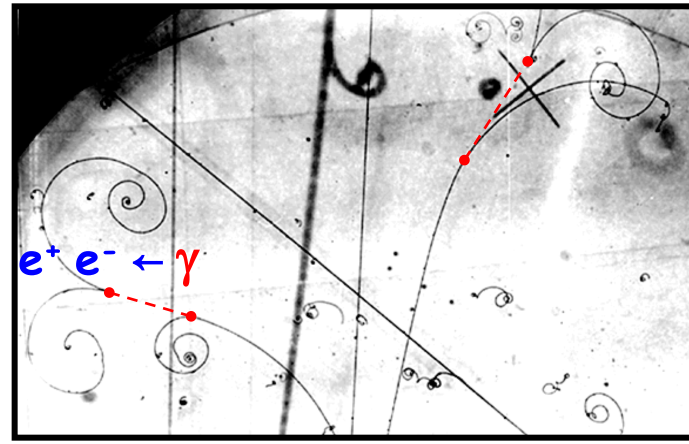
kinetic energy
non-relativistic: $E = p^2 / 2m$

relativistic: $E^2 = p^2 + m^2$
$E = \pm\sqrt{p^2 + m^2}$
electrons + ... ?

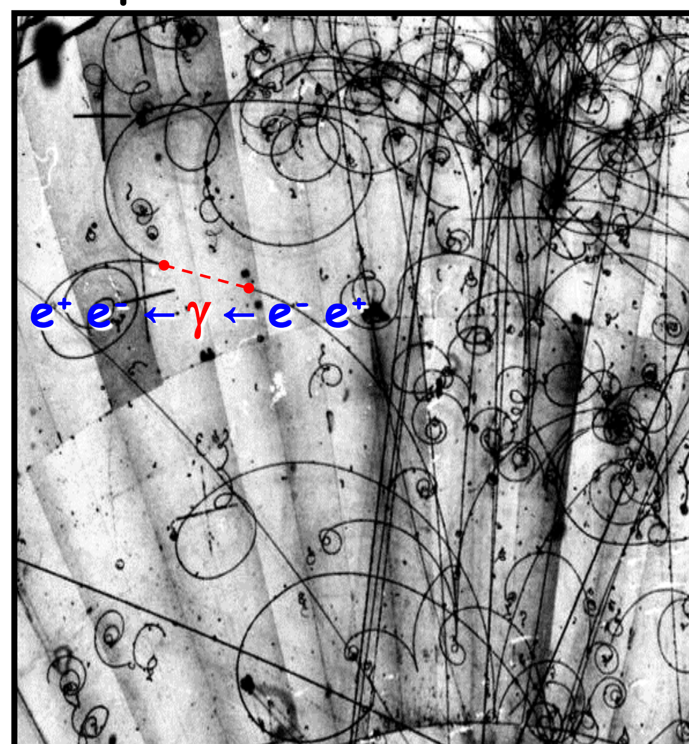
holes = antimatter = positron
another mirror world: supersymmetry?

Nobel prize  **1933**

bremsstrahlung



positron annihilation



Dirac: „The equation was smarter than I was."
P.A.M. Dirac, Proc. Royal Soc. A117 610 (1928), A126 360 (1930).

The Muon

1935: H. Yukawa:
carrier of nuclear force
mass ~200 MeV (between e + p)

Nobel prize 1949

J.C. Street, E.C. Stevenson,

New Evidence for the Existence of a Particle of Mass Intermediate between the Proton and the Electron, Phys. Rev. 52, 1003 (1937).

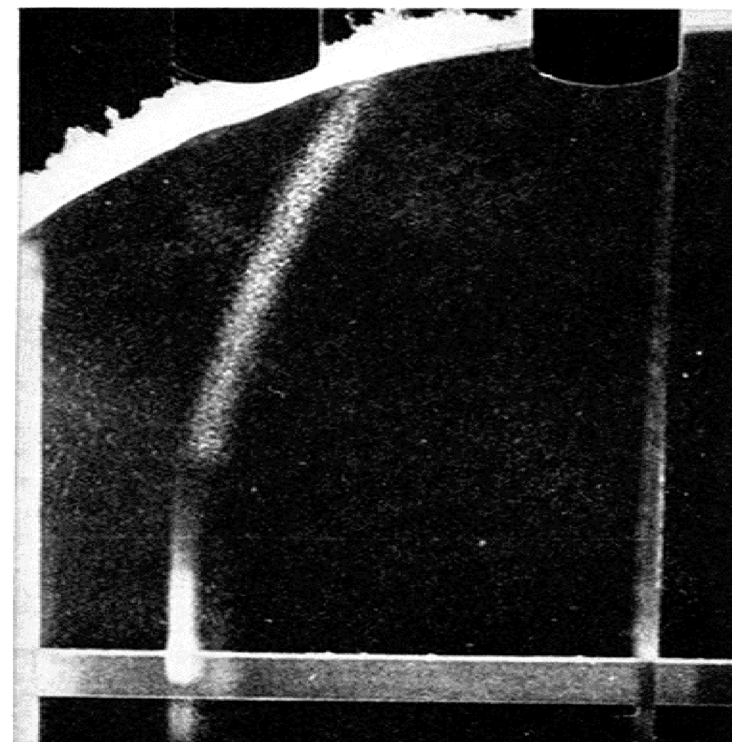
Too penetrating - NOT the Yukawa particle !

I.I. Rabi  Nobel 1944

Who ordered that ?

curvature R in magnetic field B:
R ~ p ~ 1/B

ionization I ~ velocity β = v/c:
I ~ 1/β ~ 1/(p/m)

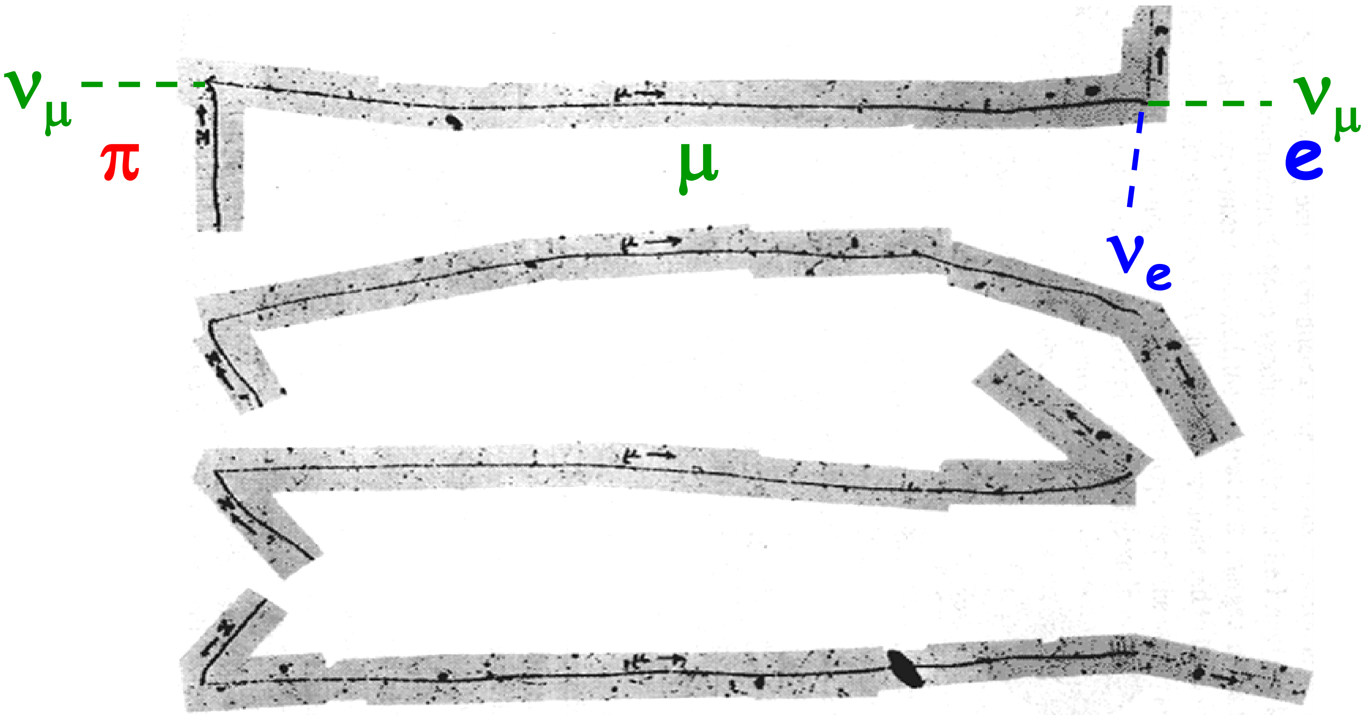


I got what I wanted,
but it wasn't what I expected.

William Hamilton, New Yorker Cartoon, October 23, 1978

The Pion

- stopping track + typical decay cascade
- decay product fixed range in nuclear emulsion = always same E
- two body decay to muon + neutrino



Nobel prize 1948:
Nobel prize 1950:

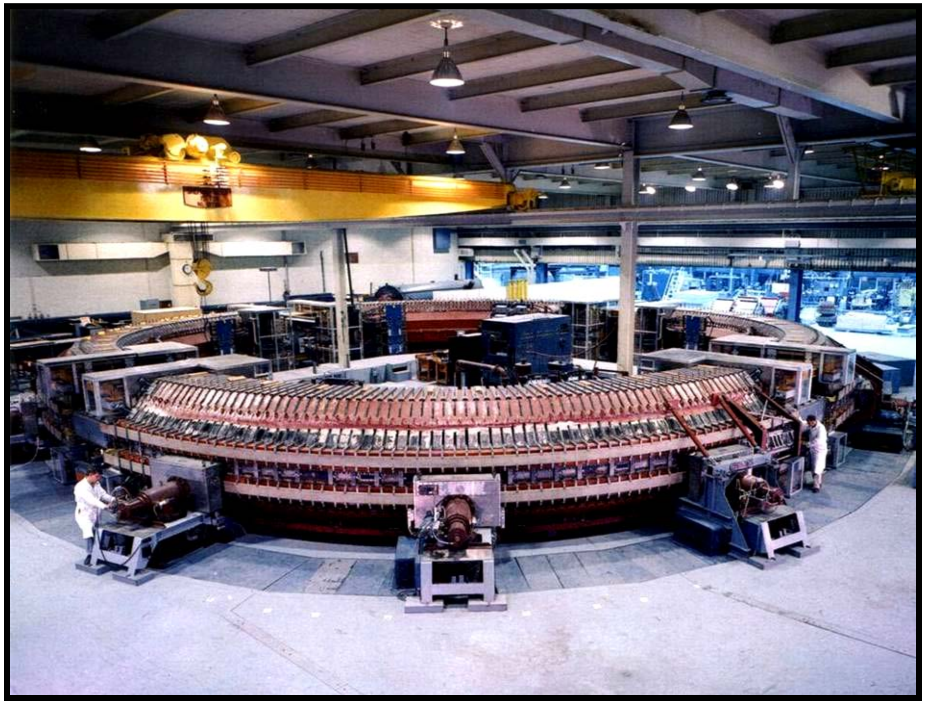
P. Blackett, Use of cloud chambers in cosmic radiation
C.F. Powell, Discoveries on mesons with emulsions

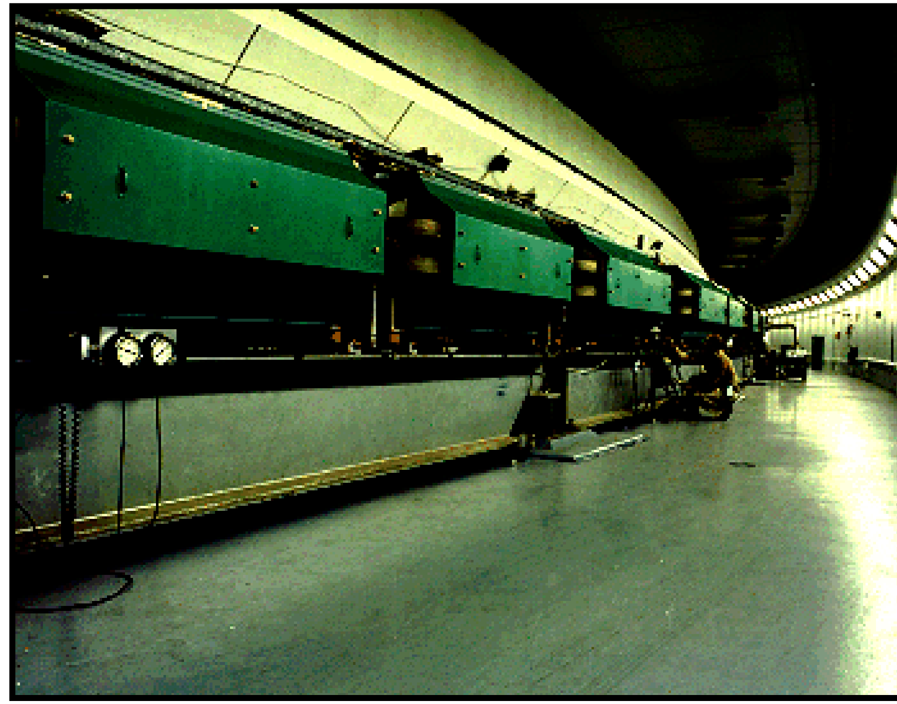
(still used, τ in OPERA, Gran Sasso)

Accelerators

find particle zoo:

BNL Brookhaven National Lab., USA

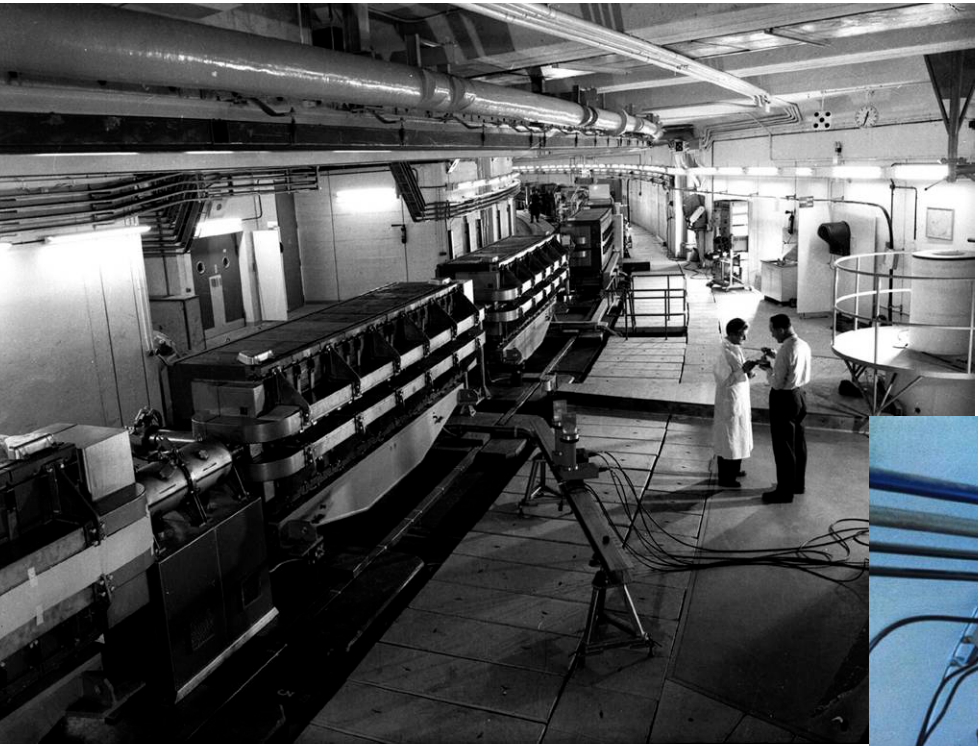




Cosmotron: 1st proton synchrotron.
1953: 3.3 GeV

AGS: Alternating Gradient Synchrotron
1960: 33 GeV

CERN Accelerators



CERN 1959:

26 GeV

Proton Synchrotron

CERN 1976:

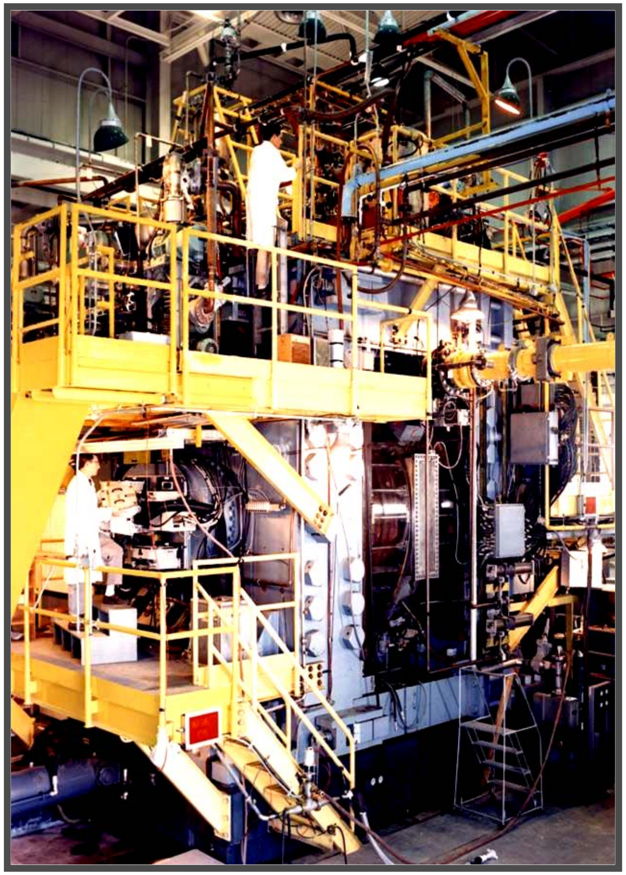
400 GeV   7 km

Super Proton Synchrotron

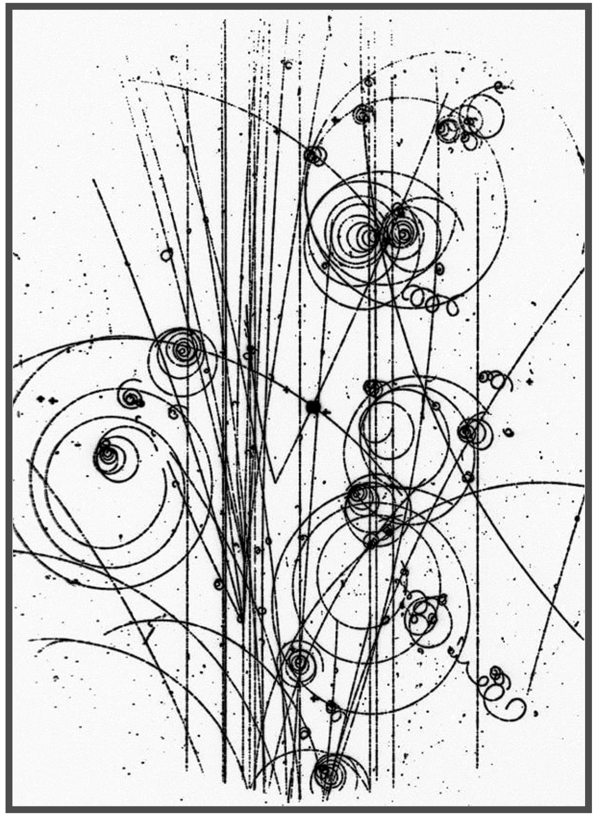
injector chain PS → SPS → LHC

Bubble Chambers

Particle



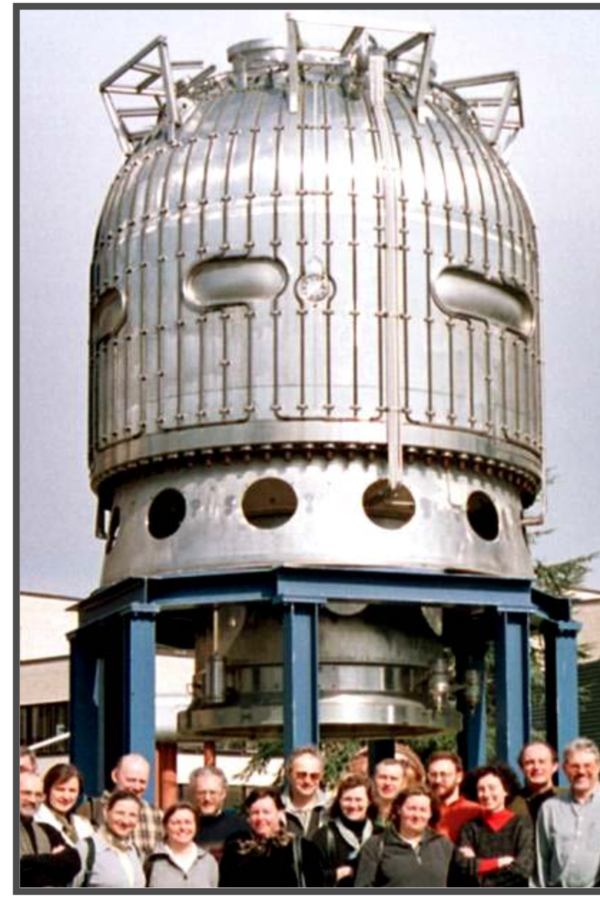
BNL 80" Bubble Chamber
1963-74
1964 Ω^-
Nobel prize



Zoo

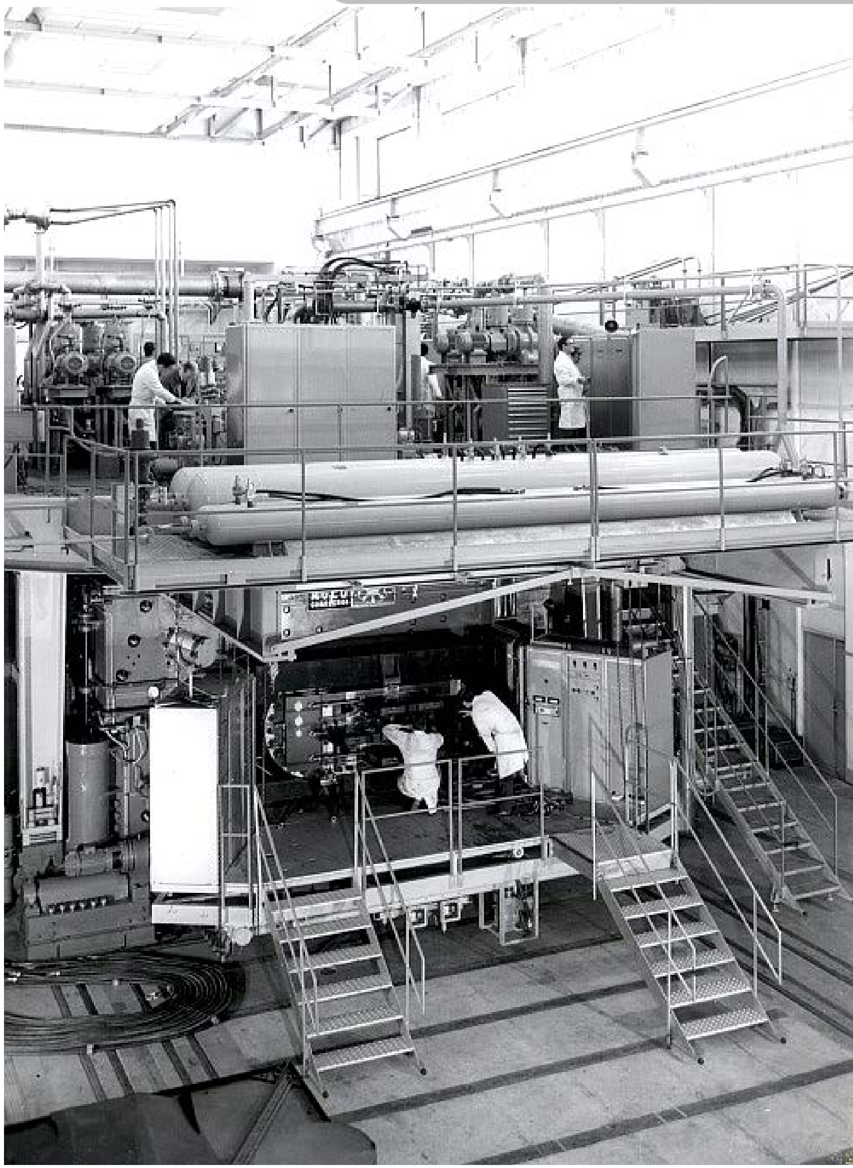
Quark model !

~100 million photos
US + EU

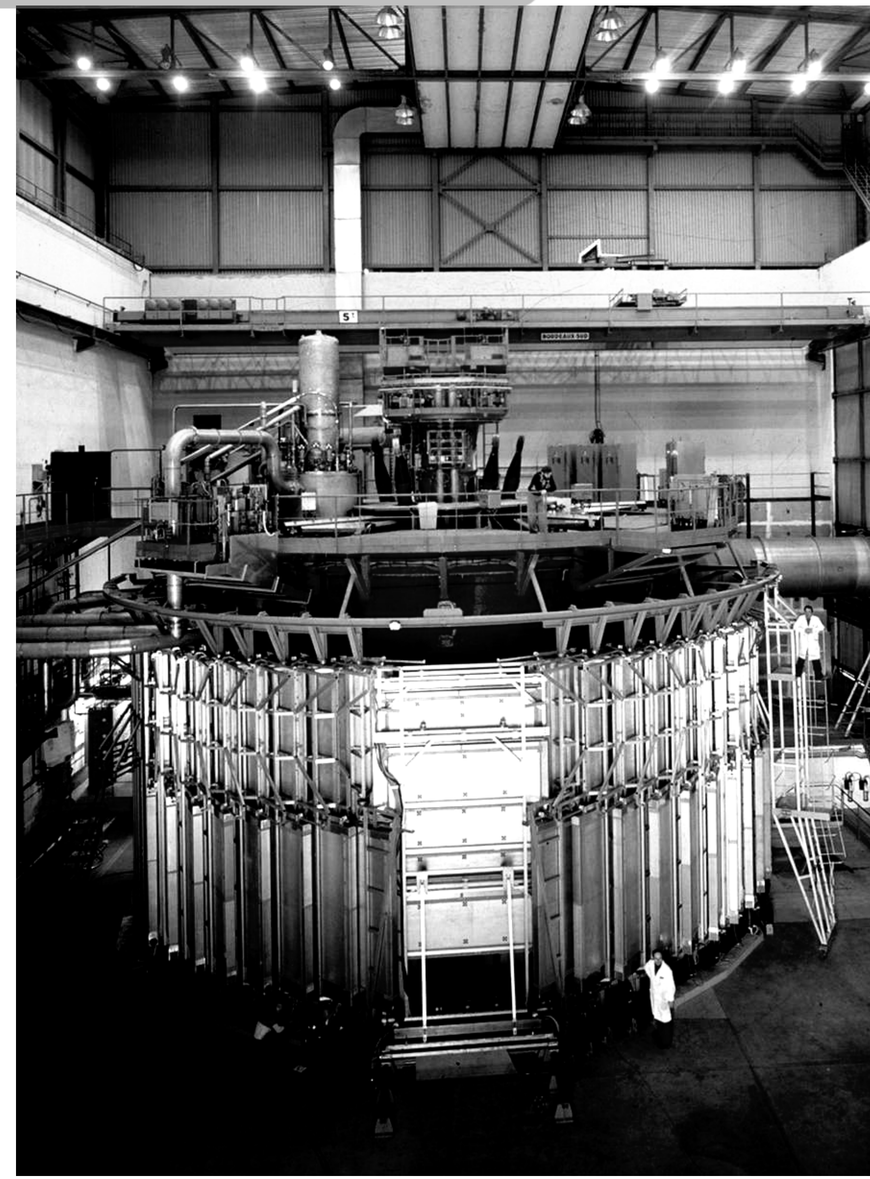


CERN: BEBC
Big European Bubble Chamber
3.7 m, 35 m^3 H, D, Ne.
6 million photos 1973-84.
piston 2 t. magnet 3.5 T, 0.8 GJ

CERN Bubble Chambers



2m Hydrogen Bubble Chamber



Big European Bubble Chamber: 20 m³

Strangeness

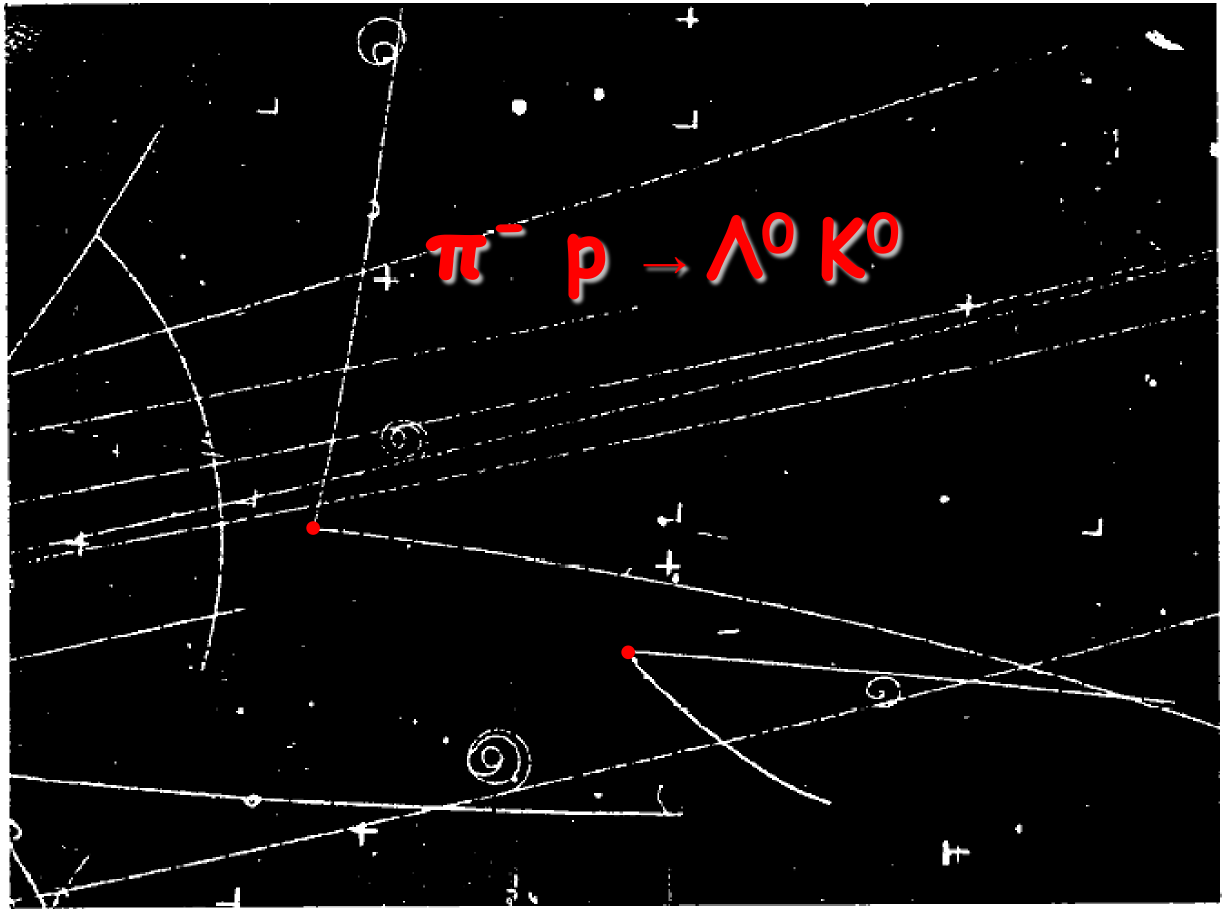


Fig. 12. Associated production, $\pi^- + p \rightarrow \Lambda^\circ + K^\circ$ at about 1 GeV with subsequent decays in Alvarez's hydrogen bubble chamber.

Gell-Mann 1953:

Strange particles:

always
pair produced
in strong interactions:

new
conservation law !

life time $\tau \sim 10^{-8...-10}$ s
decay length $c\tau \sim$ cm...m

D. Glaser, Nobel prize 1960 invention of bubble chambers
L. Alvarez, 1968 use of bubble chambers

Particle Types

LEPTONS
B=0 L=1

fundamental fermions
no strong interaction
no substructure
spin = 1/2

ELECTRONS
Q=1

e m = 511 keV
μ 106 MeV
τ 1.8 GeV

NEUTRINOS
Q=0

ν_e m $\lesssim$ 1 eV
ν_μ
ν_τ

HADRONS
L=0

B baryon nr
L lepton nr
S strangeness

BARYONS
B=1

NUCLEONS
S=0

N = (n, p)

m_p = 938 MeV
$m_n - m_p$ = 1 MeV

p stable
$n \rightarrow p\, e^- \bar{\nu}_e$ τ = 886 s

HYPERONS
S≠0

Σ^+ (1189) $\rightarrow$ N π
Λ^0 (1116) $\rightarrow$ p π^-
Ξ^- (1321) $\rightarrow$ Λ π^-

$\tau \approx 10^{-10}$ s $c\tau \approx$ cm

MESONS
B=0

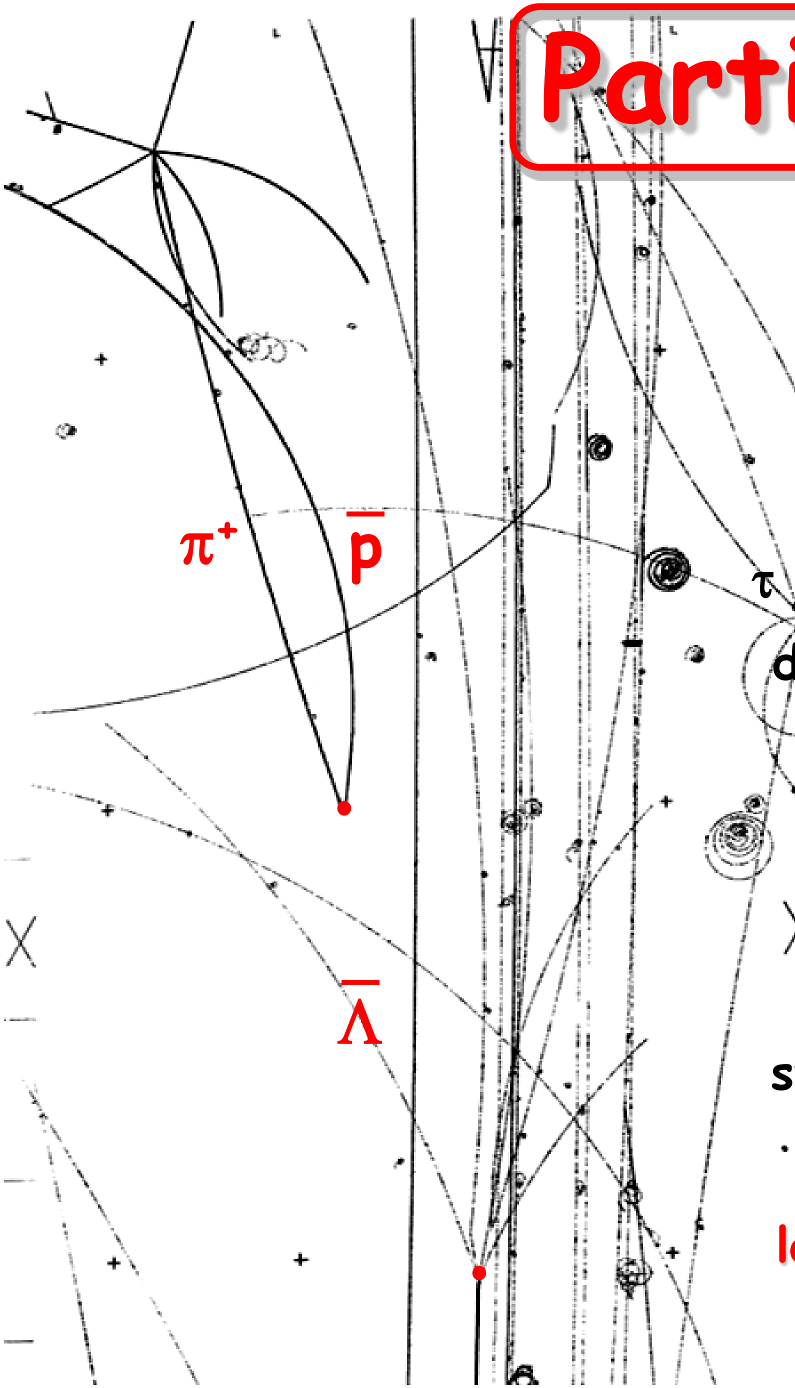
Pions = (π^+ π^0 π^-) **S=0**
$m(\pi^\pm)$ = 140 MeV
$m(\pi^0)$ = 135 MeV
$\pi^+ \rightarrow \mu^+ \nu_\mu$ τ = 26 ns $c\tau$ = 8 m

Kaons = (K^+ K^0) , (K^- $\bar{K}^0$) **S=1**

$m(K^\pm)$ = 494 MeV
$m(K^0)$ = 498 MeV
$K^+ \rightarrow \mu^+ \nu_\mu$ τ = 12 ns $c\tau$ = 3 m

2. Quark Model

Particle Zoo



weak decays

lifetime

$\tau \sim 10^{-8\ldots-10}$ s

decay length

$c\tau \sim$ cm…m

$\Delta S = 1$

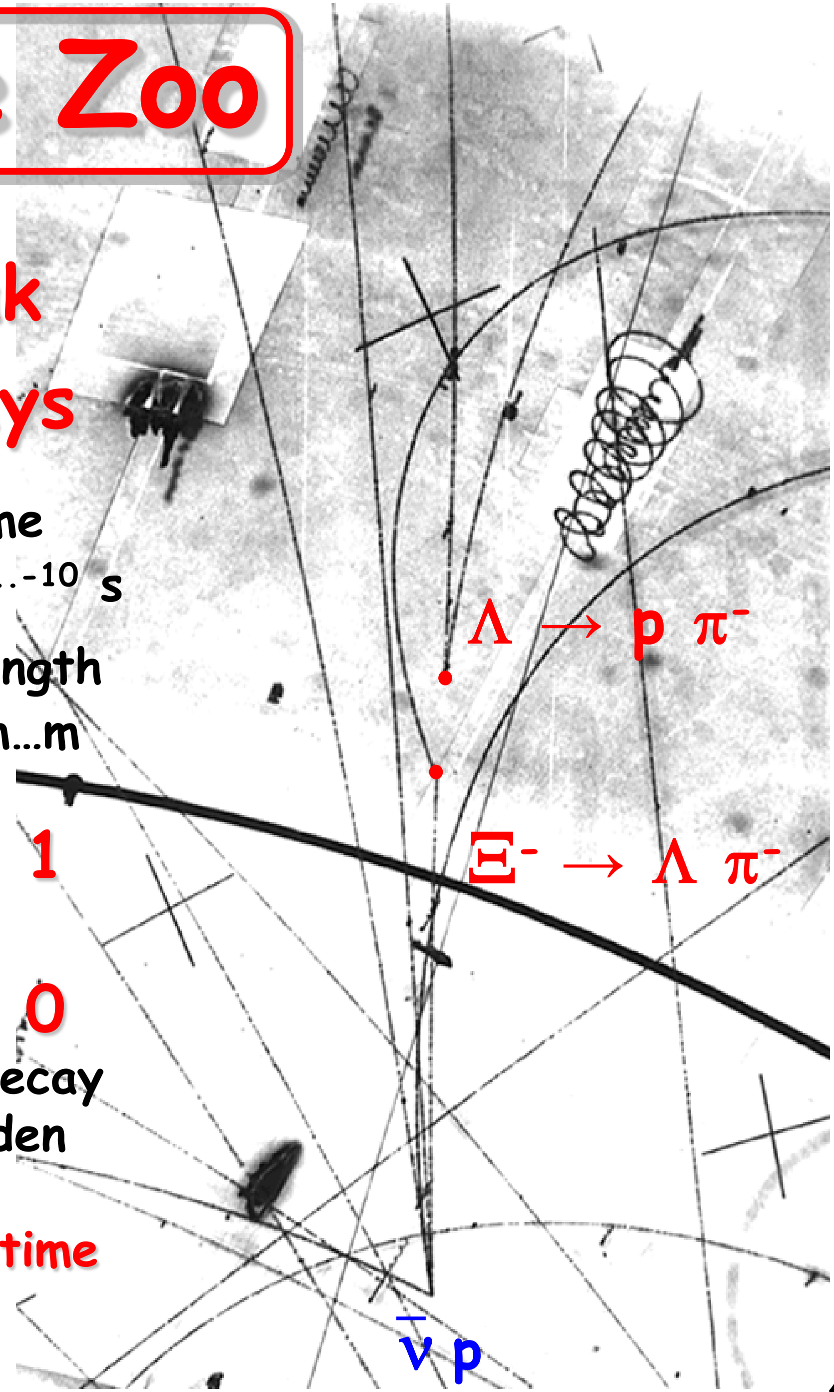
X

$\Delta S \neq 0$

strong decay forbidden

=>

long lifetime



The Particle Zoo

Light Mesons

$n\,^{2s+1}\ell_J$	J^{PC}	I = 1 $u\bar{d}$, $\bar{u}d$, $\frac{1}{\sqrt{2}}(d\bar{d}-u\bar{u})$	I = $\frac{1}{2}$ $u\bar{s}$, $d\bar{s}$; $\bar{d}s$, $-\bar{u}s$	I = 0 f'	I = 0 f	θ_{quad} [°]	θ_{lin} [°]
$1\,^1S_0$	0^{-+}	π	K	η	$\eta'(958)$	−11.5	−24.6
$1\,^3S_1$	1^{--}	$\rho(770)$	$K^*(892)$	$\phi(1020)$	$\omega(782)$	38.7	36.0
$1\,^1P_1$	1^{+-}	$b_1(1235)$	K_{1B}†	$h_1(1380)$	$h_1(1170)$		
$1\,^3P_0$	0^{++}	$a_0(1450)$	$K_0^*(1430)$	$f_0(1710)$	$f_0(1370)$		
$1\,^3P_1$	1^{++}	$a_1(1260)$	K_{1A}†	$f_1(1420)$	$f_1(1285)$		
$1\,^3P_2$	2^{++}	$a_2(1320)$	$K_2^*(1430)$	$f_2'(1525)$	$f_2(1270)$	29.6	28.0
$1\,^1D_2$	2^{-+}	$\pi_2(1670)$	$K_2(1770)$†	$\eta_2(1870)$	$\eta_2(1645)$		
$1\,^3D_1$	1^{--}	$\rho(1700)$	$K^*(1680)$‡		$\omega(1650)$		
$1\,^3D_2$	2^{--}		$K_2(1820)$‡				
$1\,^3D_3$	3^{--}	$\rho_3(1690)$	$K_3^*(1780)$	$\phi_3(1850)$	$\omega_3(1670)$	32.0	31.0
$1\,^3F_4$	4^{++}	$a_4(2040)$	$K_4^*(2045)$		$f_4(2050)$		
$1\,^3G_5$	5^{--}	$\rho_5(2350)$					
$1\,^3H_6$	6^{++}	$a_6(2450)$			$f_6(2510)$		
$2\,^1S_0$	0^{-+}	$\pi(1300)$	$K(1460)$	$\eta(1475)$	$\eta(1295)$	−22.4	−22.6
$2\,^3S_1$	1^{--}	$\rho(1450)$	$K^*(1410)$‡	$\phi(1680)$	$\omega(1420)$		

LIGHT UNFLAVORED ($S = C = B = 0$)

	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$	• $\pi_2(1670)$	$1^-(2^{-+})$
• π^0	$1^-(0^{-+})$	• $\phi(1680)$	$0^-(1^{--})$
• η	$0^+(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$
• $f_0(600)$	$0^+(0^{++})$	• $\rho(1700)$	$1^+(1^{--})$
• $\rho(770)$	$1^+(1^{--})$	$a_2(1700)$	$1^-(2^{++})$
• $\omega(782)$	$0^-(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$
• $\eta'(958)$	$0^+(0^{-+})$	$\eta(1760)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$	• $\pi(1800)$	$1^-(0^{-+})$
• $a_0(980)$	$1^-(0^{++})$	$f_2(1810)$	$0^+(2^{++})$
• $\phi(1020)$	$0^-(1^{--})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $h_1(1170)$	$0^-(1^{+-})$	$\eta_2(1870)$	$0^+(2^{-+})$
• $b_1(1235)$	$1^+(1^{+-})$	$\rho(1900)$	$1^+(1^{--})$
• $a_1(1260)$	$1^-(1^{++})$	$f_2(1910)$	$0^+(2^{++})$
• $f_2(1270)$	$0^+(2^{++})$	• $f_2(1950)$	$0^+(2^{++})$
• $f_1(1285)$	$0^+(1^{++})$	$\rho_3(1990)$	$1^+(3^{--})$
• $\eta(1295)$	$0^+(0^{-+})$	• $f_2(2010)$	$0^+(2^{++})$
• $\pi(1300)$	$1^-(0^{-+})$	$f_0(2020)$	$0^+(0^{++})$
• $a_2(1320)$	$1^-(2^{++})$	• $a_4(2040)$	$1^-(4^{++})$
• $f_0(1370)$	$0^+(0^{++})$	• $f_4(2050)$	$0^+(4^{++})$
$h_1(1380)$	$?^-(1^{+-})$	$\pi_2(2100)$	$1^-(2^{-+})$
• $\pi_1(1400)$	$1^-(1^{-+})$	$f_0(2100)$	$0^+(0^{++})$
• $\eta(1405)$	$0^+(0^{-+})$	$f_2(2150)$	$0^+(2^{++})$
• $f_1(1420)$	$0^+(1^{++})$	$\rho(2150)$	$1^+(1^{--})$
• $\omega(1420)$	$0^-(1^{--})$	$f_0(2200)$	$0^+(0^{++})$
$f_2(1430)$	$0^+(2^{++})$	$f_J(2220)$	$0^+(2^{++}$ or $4^{++})$
• $a_0(1450)$	$1^-(0^{++})$		
• $\rho(1450)$	$1^+(1^{--})$	$\eta(2225)$	$0^+(0^{-+})$
• $\eta(1475)$	$0^+(0^{-+})$	$\rho_3(2250)$	$1^+(3^{--})$
• $f_0(1500)$	$0^+(0^{++})$	• $f_2(2300)$	$0^+(2^{++})$
$f_1(1510)$	$0^+(1^{++})$	$f_4(2300)$	$0^+(4^{++})$
• $f_2'(1525)$	$0^+(2^{++})$	• $f_2(2340)$	$0^+(2^{++})$
$f_2(1565)$	$0^+(2^{++})$	$\rho_5(2350)$	$1^+(5^{--})$
$h_1(1595)$	$0^-(1^{+-})$	$a_6(2450)$	$1^-(6^{++})$
• $\pi_1(1600)$	$1^-(1^{-+})$	$f_6(2510)$	$0^+(6^{++})$
$a_1(1640)$	$1^-(1^{++})$	**OTHER LIGHT**	
$f_2(1640)$	$0^+(2^{++})$	Further States	
• $\eta_2(1645)$	$0^+(2^{-+})$		
• $\omega(1650)$	$0^-(1^{--})$		
• $\omega_3(1670)$	$0^-(3^{--})$		

STRANGE ($S = \pm1$, $C = B = 0$)

	$I(J^P)$
• $K^\pm$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K_S^0	$1/2(0^-)$
• K_L^0	$1/2(0^-)$
$K_0^*(800)$	$1/2(0^+)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K_0^*(1430)$	$1/2(0^+)$
• $K_2^*(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
$K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K_3^*(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K_0^*(1950)$	$1/2(0^+)$
$K_2^*(1980)$	$1/2(2^+)$
• $K_4^*(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K_5^*(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED ($C = \pm1$)

• $D^\pm$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^\pm$	$1/2(1^-)$
• $D_1(2420)^0$	$1/2(1^+)$
$D_1(2420)^\pm$	$1/2(?^?)$
• $D_2^*(2460)^0$	$1/2(2^+)$
• $D_2^*(2460)^\pm$	$1/2(2^+)$
$D^*(2640)^\pm$	$1/2(?^?)$

CHARMED, STRANGE ($C = S = \pm1$)

• $D_s^\pm$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D_{sJ}^*(2317)^\pm$	$0(0^+)$
• $D_{sJ}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{s2}(2573)^\pm$	$0(?^?)$

BOTTOM ($B = \pm1$)

	$I^G(J^{PC})$
• $B^\pm$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^\pm/B^0$ ADMIXTURE	
• $B^\pm/B^0/B_s^0/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
• B^*	$1/2(1^-)$
$B_J^*(5732)$	$?(?^?)$

BOTTOM, STRANGE ($B = \pm1$, $S = \mp1$)

• B_s^0	$0(0^-)$
B_s^*	$0(1^-)$
$B_{sJ}^*(5850)$	$?(?^?)$

BOTTOM, CHARMED ($B = C = \pm1$)

• $B_c^\pm$	$0(0^-)$

$c\bar{c}$

• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
$h_c(1P)$	$?^?(?^{??})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
$\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
$\psi(3836)$	$0^-(2^{--})$
$X(3872)$	$?^?(?^?)$
• $\psi(4040)$	$0^-(1^{--})$
• $\psi(4160)$	$0^-(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$

$b\bar{b}$

$\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
• $\Upsilon(2S)$	$0^-(1^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\Upsilon(4S)$	$0^-(1^{--})$
• $\Upsilon(10860)$	$0^-(1^{--})$
• $\Upsilon(11020)$	$0^-(1^{--})$

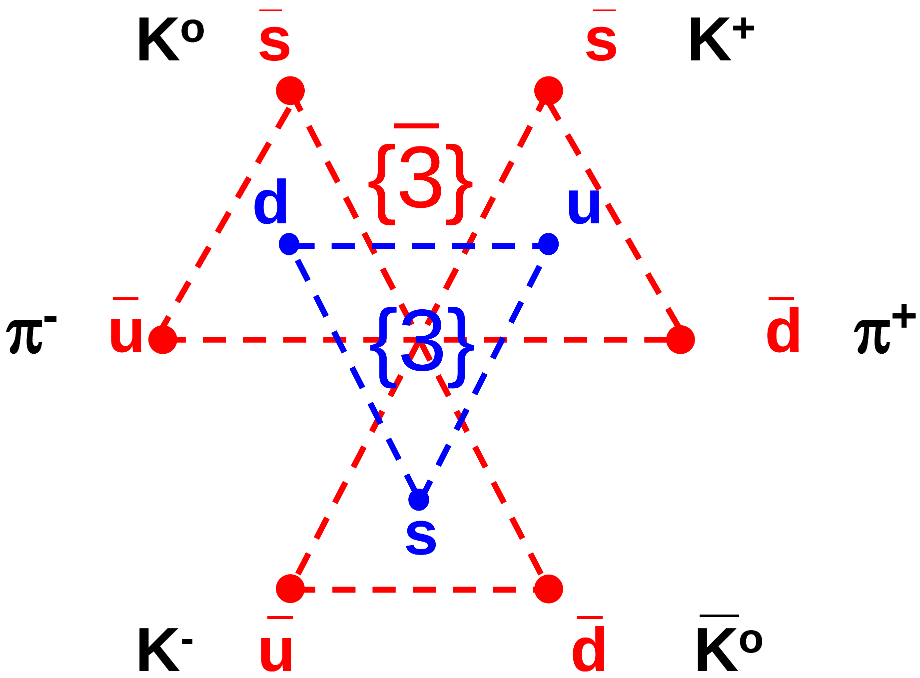
NON-$q\bar{q}$ CANDIDATES

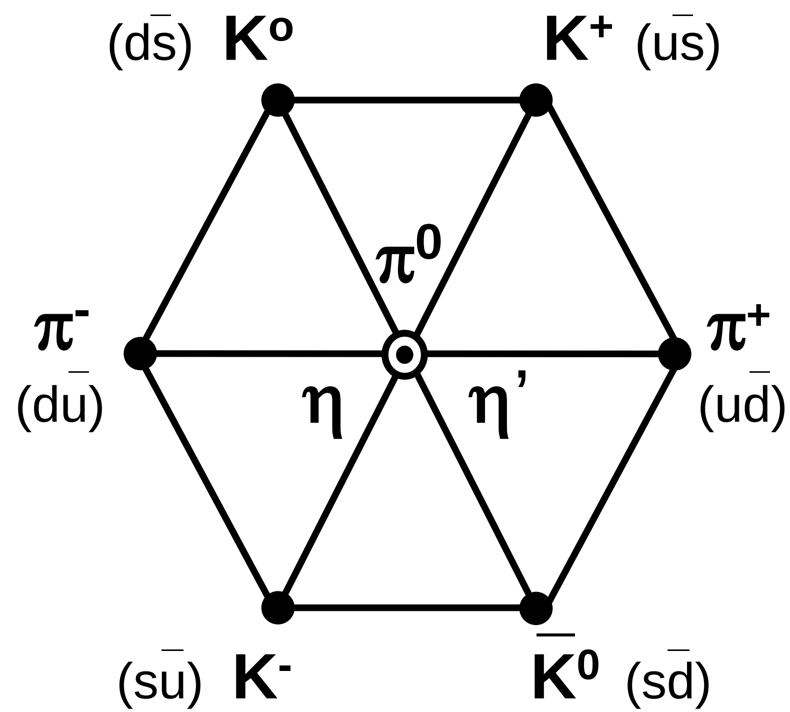
NON-$q\bar{q}$ CANDIDATES

Meson Octet

$$\{q\} \otimes \{\bar{q}\} = \nabla \otimes \Delta = \{2\} \otimes \{\bar{2}\} = \{1\} \oplus \{3\} \quad \text{in SU(2)}$$

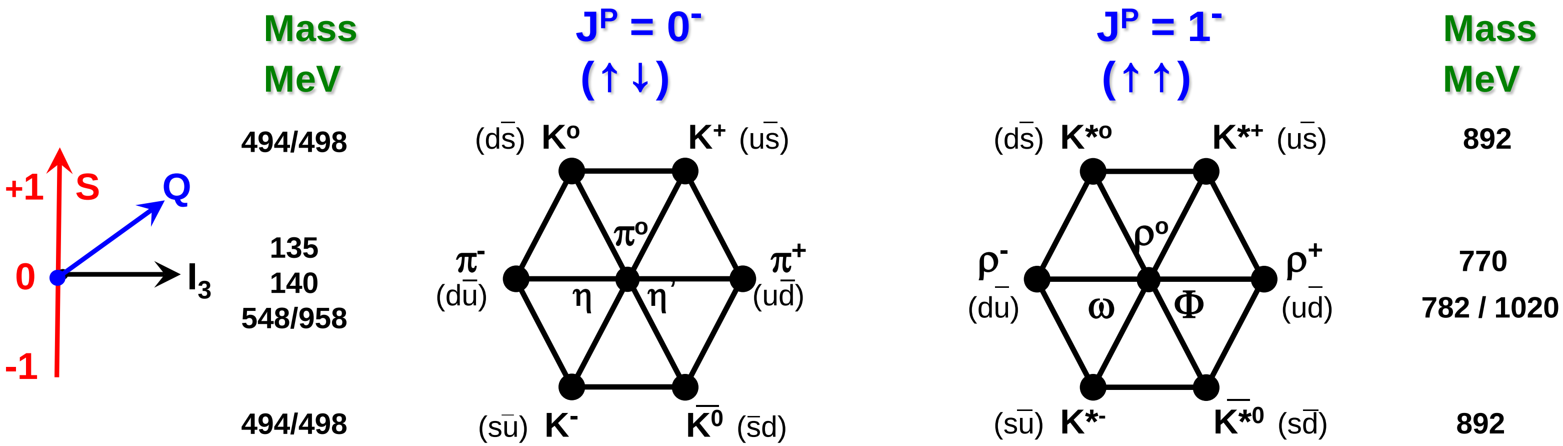
$$= \{3\} \otimes \{\bar{3}\} = \{1\} \oplus \{8\} \quad \text{in SU(3)}$$



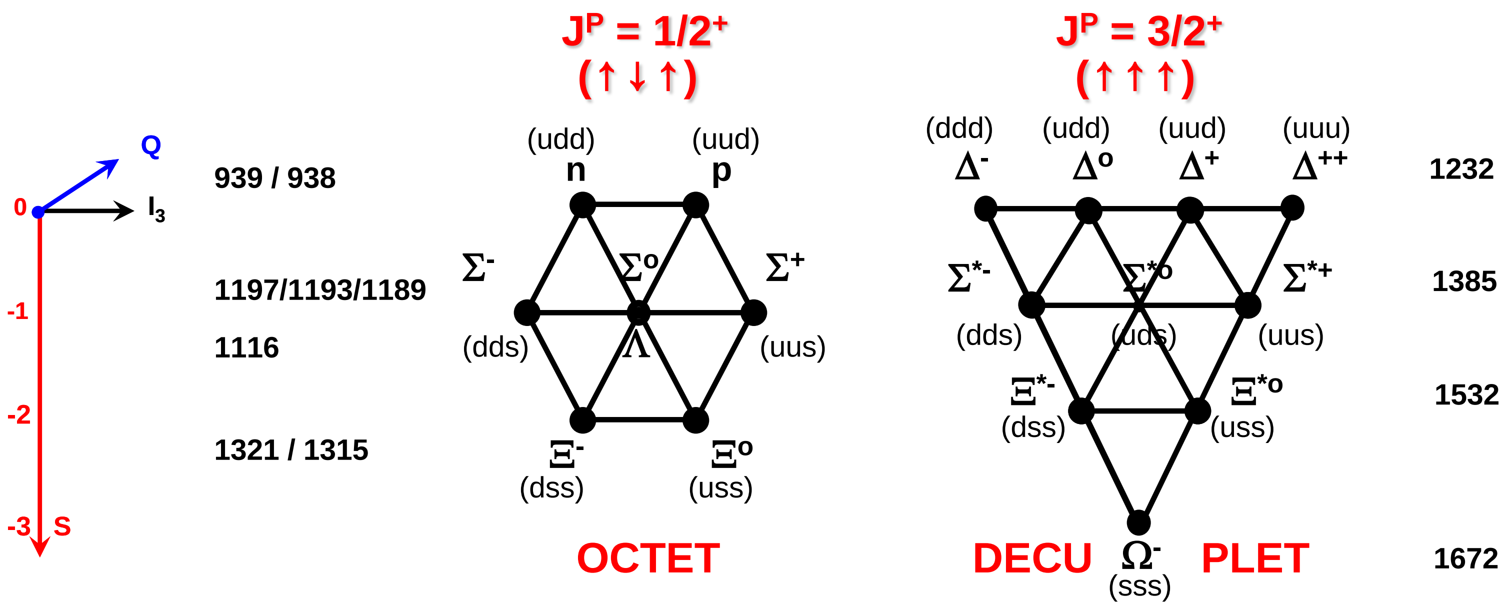


The Quark Model

MESONS



BARYONS



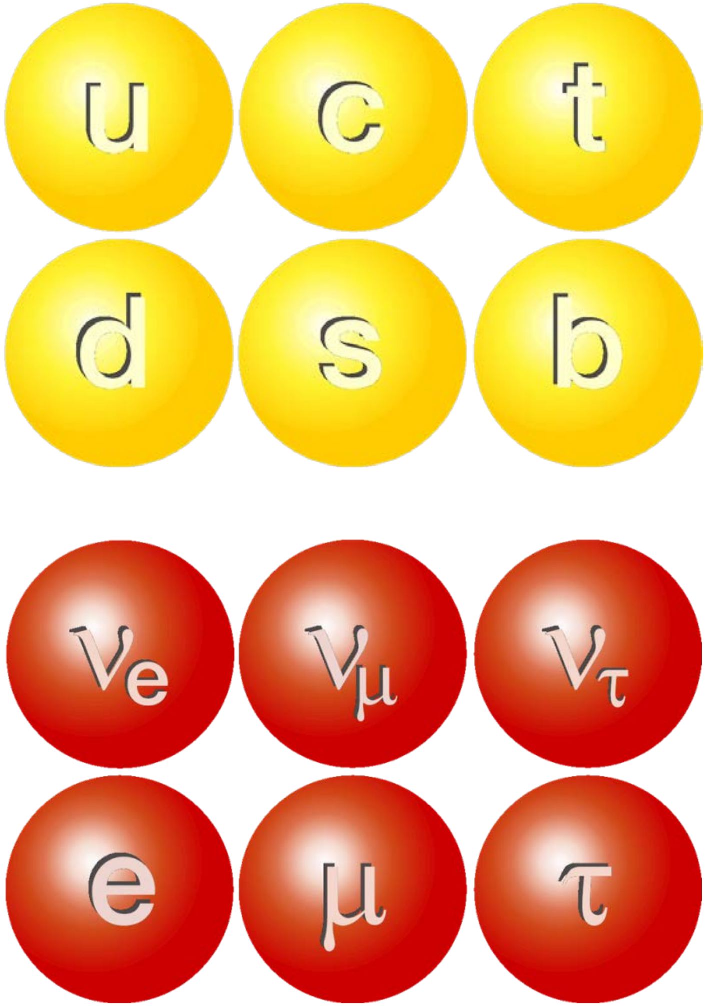
The Building Blocks

Great scheme,

BUT:

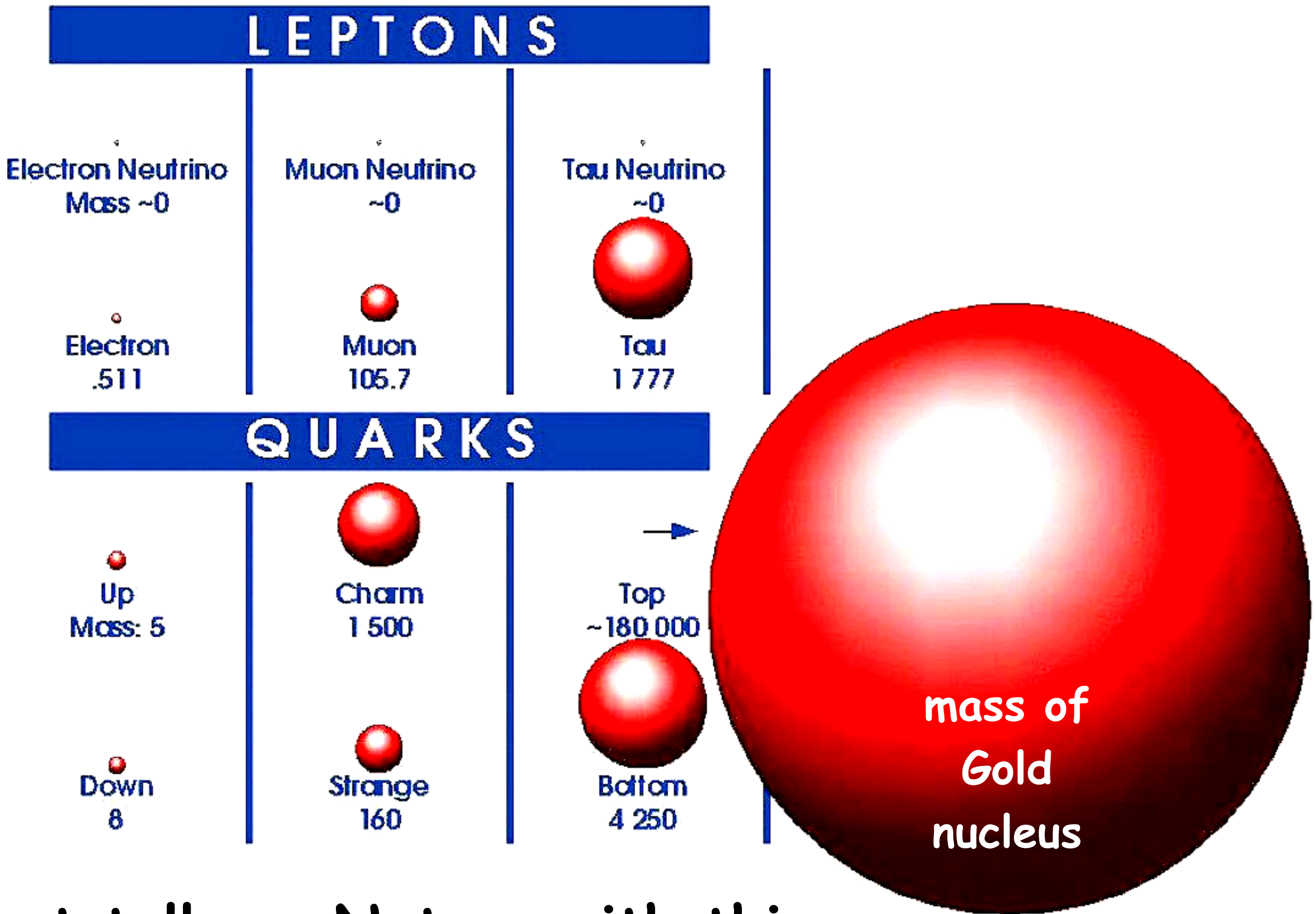
all 3 symmetries mysterious:

- up-down ((weak) isospin)
- lepton-quark
- 3 families



PARTICLES					FORCES			
					Electro-Magnet.	Weak	Nuclear	Gravi-tation
		Charge			Electric	Weak	Color	Mass
		Symmetry			U(1)	SU(2)	SU(3)	
Matter Particles	Fermions J=1/2							
Quarks	Up	u	c	t	+2/3	I_W, Y_W	r g b	
	Down	d	s	b	-1/3			
Leptons	Electrons	e	μ	τ	-1	I_W, Y_W		
	Neutrinos	ν_e	ν_μ	ν_τ	0			
Force Particles	Bosons J=1							
Photon		γ						
Weak Bosons		W^+, Z^0, W^-						
Gluons		8 g_{ij}						
Graviton	(J=2)	G						

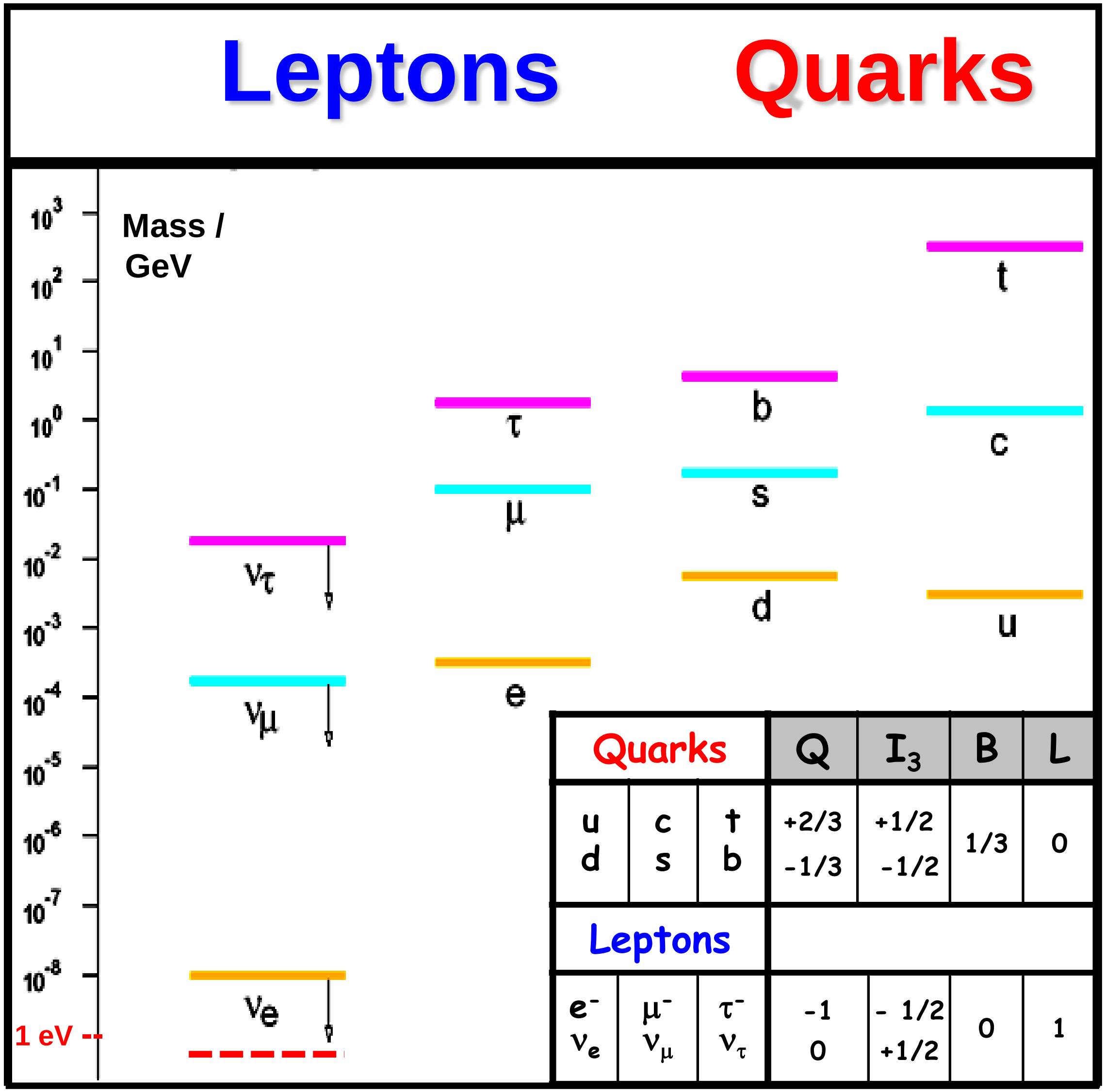
Fermion Mass Spectrum



What tells us Nature with this

new spectroscopy ?

Fermion Mass Spectrum



Quarks			Q	I_3	B	L
u d	c s	t b	+2/3 -1/3	+1/2 -1/2	1/3	0
Leptons						
e^- ν_e	μ^- ν_μ	τ^- ν_τ	-1 0	- 1/2 +1/2	0	1

PLANCK, KATRIN, $0\nu 2\beta$

What tells us **Nature** with this **spectrum** ?

IF
$m_d < m_u$ =>
$m_n < m_p$ =>
p decay =>
neutral universe

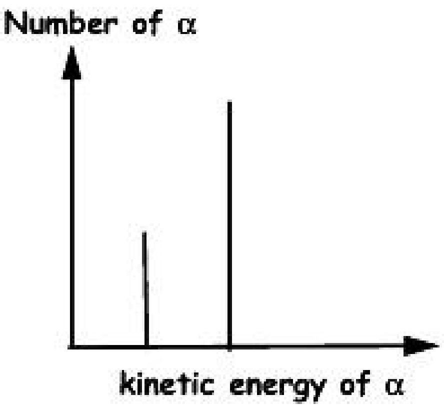
4. Weak Interaction

Neutrinos

most abundant particle in Universe (except photon)

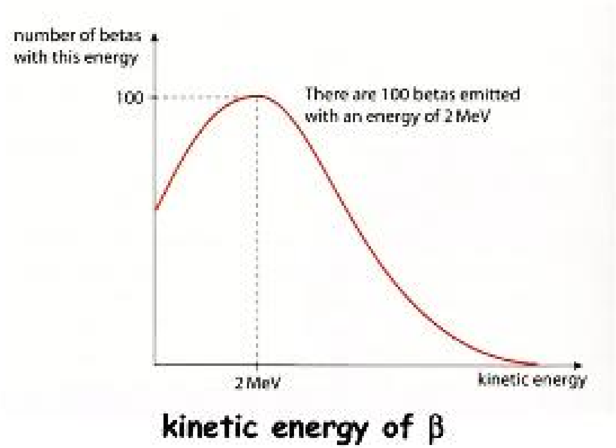
pure sources and pure probes of weak interaction

α – radiation



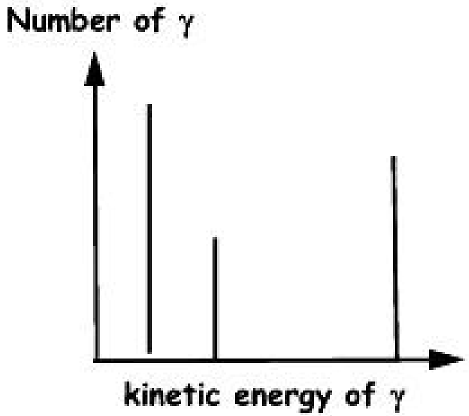
This radiation has constant energy values.

β – radiation



This radiation has not constant energy values because the kinetic energy is shared between the β and the ν.

γ – radiation



This radiation has constant energy values.

Neutrinos

Neutrinos, they are very small
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dust maids down a drafty hall
Or photons through a sheet of glass.

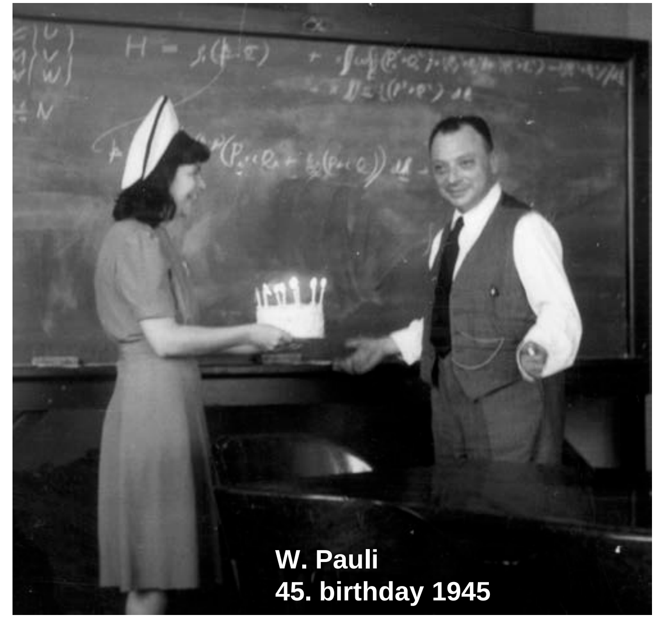
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall,
And, scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.

At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed. You call
It wonderful; I call it crass.

John Updike, Cosmic Gall. The New Yorker, 17 Dec 1960.

Pauli's Neutrino hypothesis

$n \rightarrow p\ e^-$? continuous β spectrum
E conservation violated ?



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

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Des. 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 Grossenordnung 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.

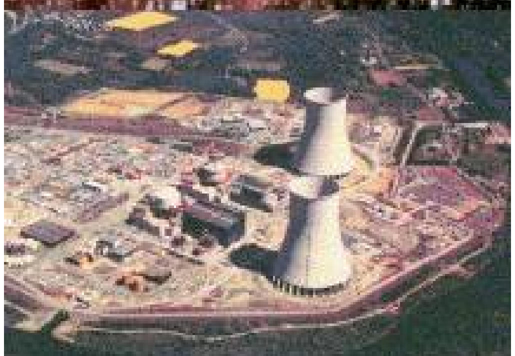
Also, liebe Radioaktive, prüfet und richtet!
Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7. Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.

$n \rightarrow p\ e^-\ \bar{\nu}_e$

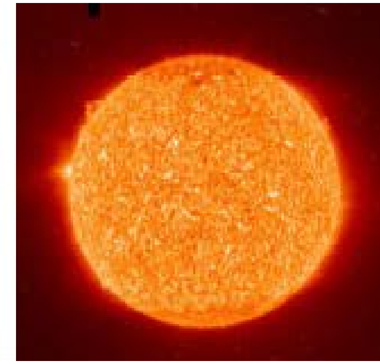
renamed
Neutrino
1933 by E. Fermi
after neutron discovery

„Heute habe ich etwas Schreckliches getan, etwas, was kein theoretischer Physiker jemals tun sollte. Ich habe etwas vorgeschlagen, was nie experimentell verifiziert werden kann."

Pauli am selben Tag an den Astronomen W.Baade

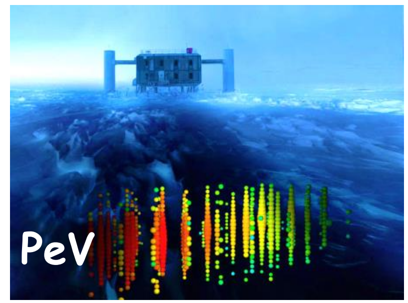


Neutrinos



Supernovae

SN 1987A: 10^{38} s^{-1}
10^{58} total
10^{14} m^{-2}
99% of E
~cosmic lumi



Sun

$6 \cdot 10^{14}$ m^{-2} s^{-1}

Reactor

$2 \cdot 10^{20}$ s^{-1} GW_{th}^{-1}
@ 10 m: 10^{17} m^{-2} s^{-1}

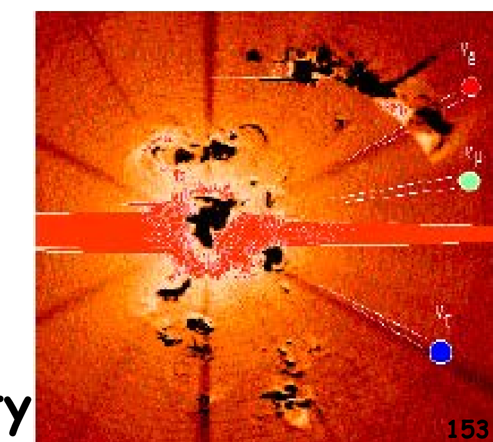
Atmospheric

10^{4} m^{-2} s^{-1}

Accelerators

Big Bang

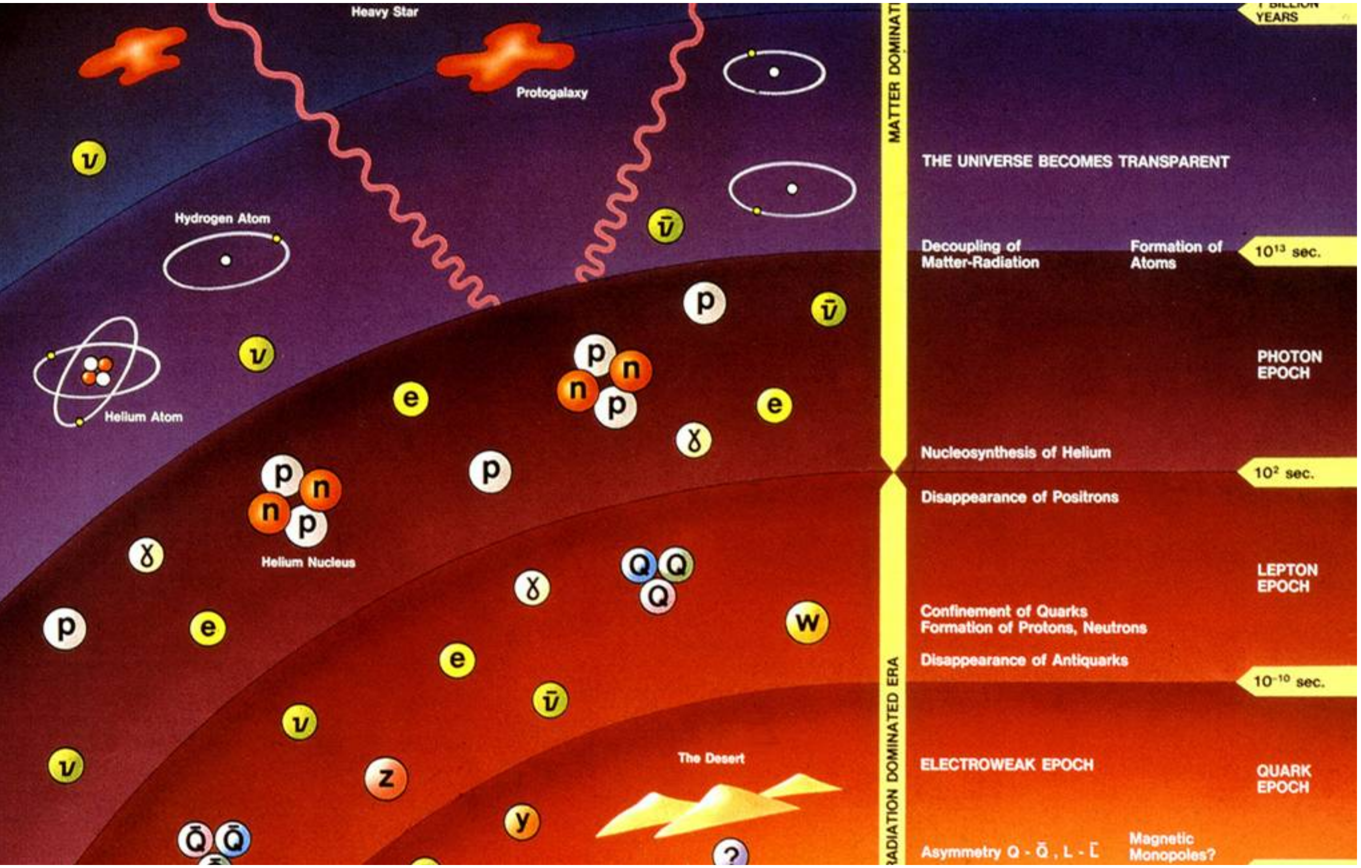
335 cm^{-3}
100 μs - 100 s
dominant cosmic energy



Earth

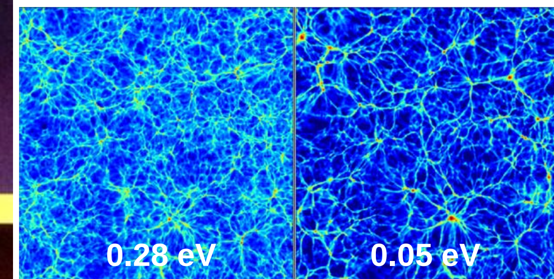
$2 \cdot 10^{11}$ m^{-2} s^{-1} radioactivity

Big Bang Neutrinos



decoupling:

γ 380.000 a



hot ν's. $m_\nu > 1$ eV wipe out small-scale cosmic structures

CMBR (PLANCK) + BAO:
$\Sigma m(\nu_i) < 0.23$ eV
$N^{eff} = 3.2 \pm 0.2$

arXiv:1502.01582, 9.
Thomas, Abdalla, Lahav, PRL 2010
Putter et al, arXiv: 1201.1909. Phys.Rep. 517(2012)141

ν 1 s $\bar{\nu}\nu \nrightarrow e^+e^-$
equilibrium till 0.2 s / 2 MeV
$\bar{\nu}_e\, p \to n\, e^+$
$n \to p\, e^-\, \bar{\nu}_e$

now: γ: 2.7 K background radiation 410/cm³ Penzias, Wilson 1964
ν: 1.9 K background radiation 336/cm³ Nobel 1978

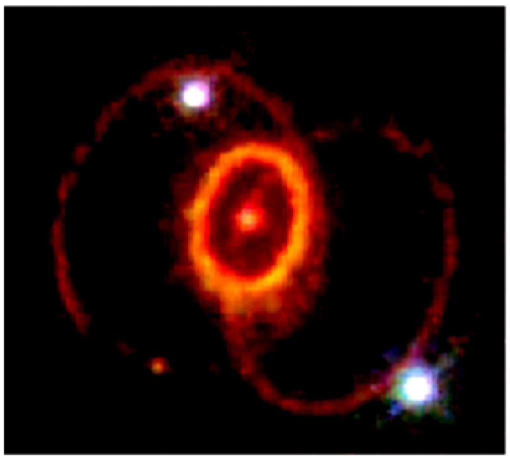
$T_\nu = (4/11)^{1/3}\, T_{CMB}$ $n_\nu = (9/11)^{1/3}\, n_{CMB}$
"dark photons": n_ν, m_ν

neutrino / baryon density: $\Omega_\nu/\Omega_b = 0.5\, \Sigma m_\nu$/eV
$\Omega_\nu h^2 = m_\nu/94\ \text{eV} < 0.0025$

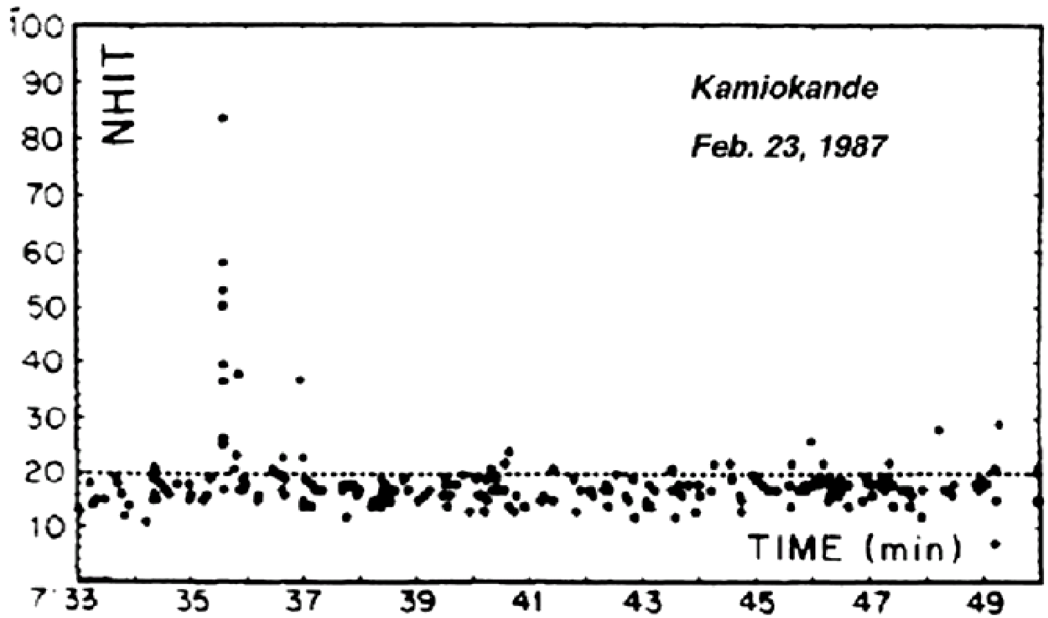
Cosmic Neutrinos

Supernova SN 1987A: Magellan cloud, 168.000 ly

10^{58} ν total, 10^{15} ν/m^2



2002



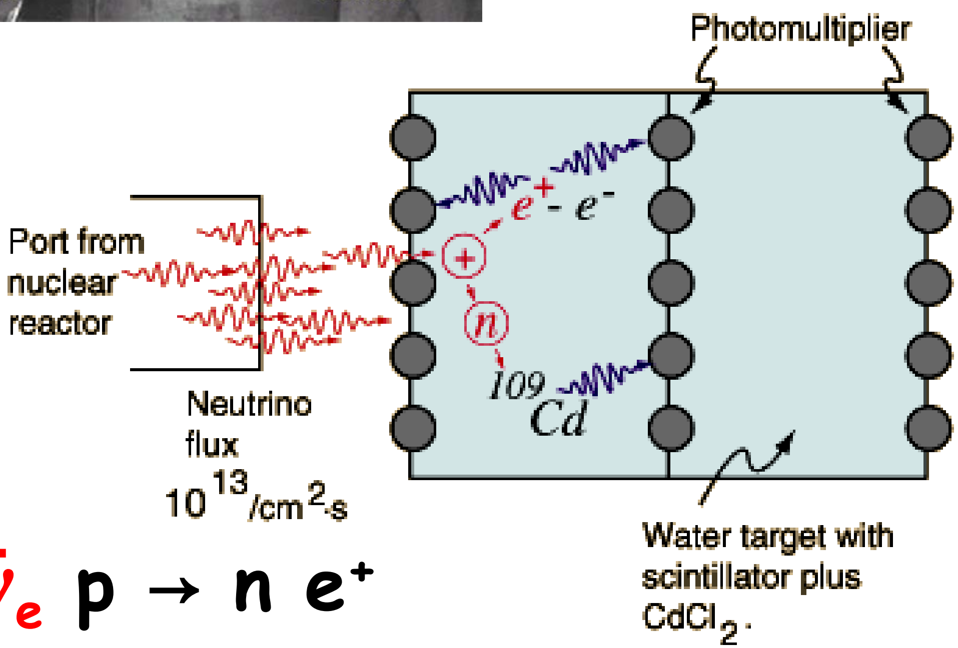
first Supernova visible by naked eye
since Kepler 1604 at 20.000 ly in Milky Way!

neutrinos seen ~2h before light => m_ν < 30 eV (Sun: light takes >10.000 yrs)

Neutrino Discovery

25 years after Pauli: Project Poltergeist:

C.Cowan and F.Reines, 1956 :
Savannah river reactor, USA



Delayed coincident detection of γ from ^{109}Cd with pair of γ's from e^+- e^- annihilation.

Reines:
Nobel prize

1995

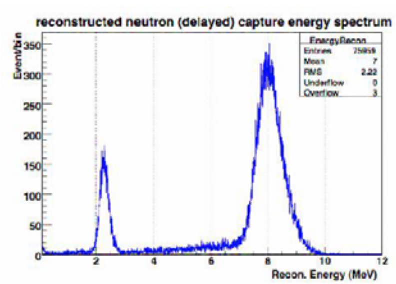
$\bar{\nu}_e \; p \rightarrow n \; e^+$

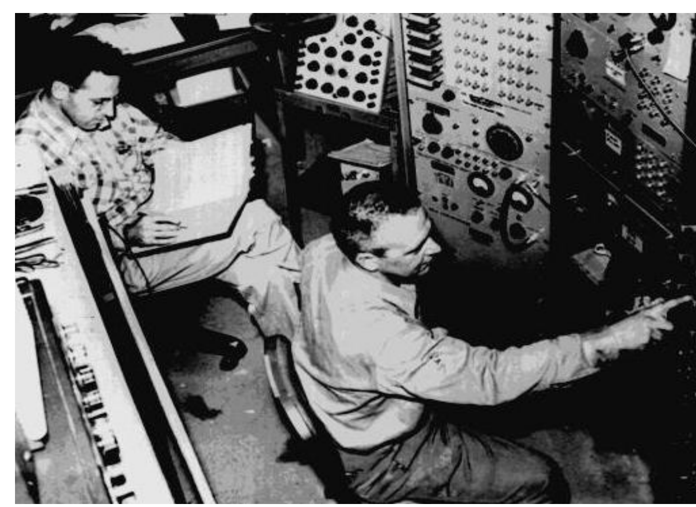
$e^+ e^- \rightarrow \gamma\gamma$ prompt, E_γ = some MeV

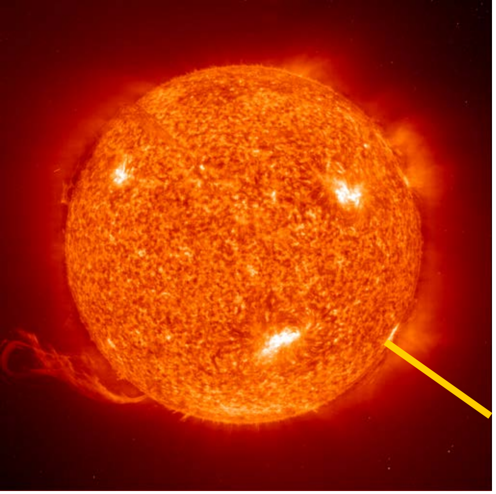
$n \; Cd \rightarrow Cd^* \gamma$

γ emission delay ~5 μs
look for γ_n–γ_e coincidences

today Gd: 16t Daya Bay, 100t SuperK







Solar Neutrinos

Homestake Gold mine

ν_e

6×10^{14} $m^{-2} s^{-1}$

nuclear fusion in the Sun :

pppp → ppnn = He

p → n e^+ ν_e

micro-radiochemistry: detect single decays

ν_e Cl^{37} → Ar^{37} e^- τ = 35 d

ν_e n → p e^-

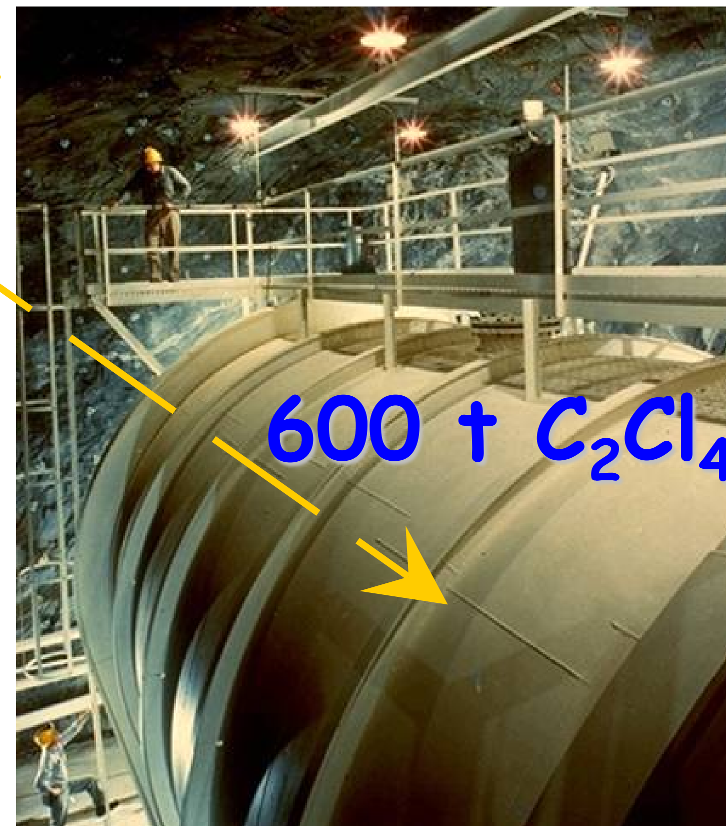
1967-94: ~ 2/3 neutrinos missing !

nuclear fission produces $\bar{\nu}_e$

1968 Savannah river reactor

$\bar{\nu}_e$ Cl^{37} $\nrightarrow$ Ar^{37} e^- no signal =>

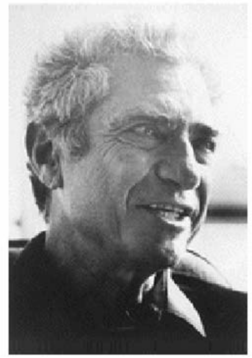
$\nu \neq \bar{\nu}$



Are neutrinos equal? The muon neutrino

L.Lederman

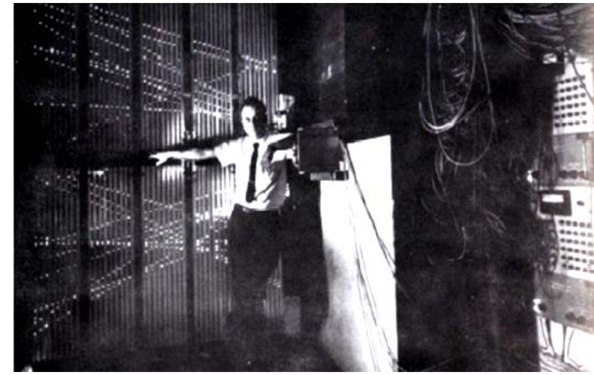
M.Schwartz

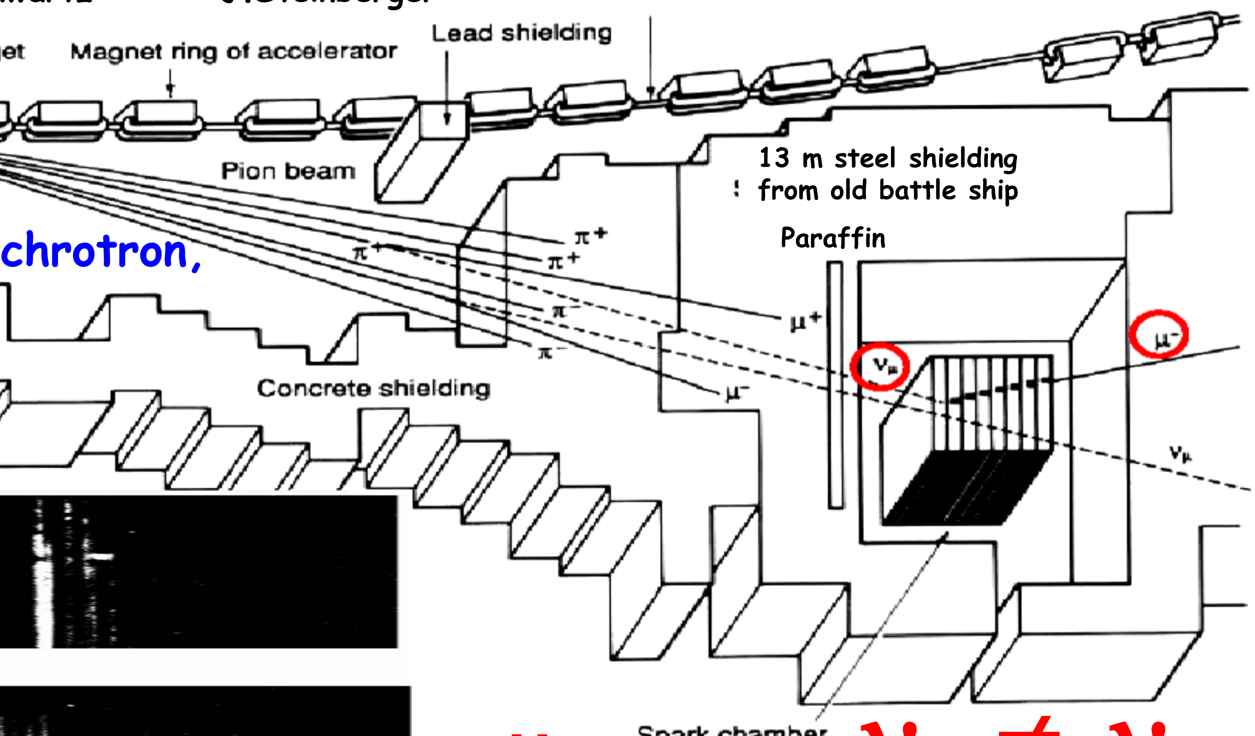


J.Steinberger

Nobel

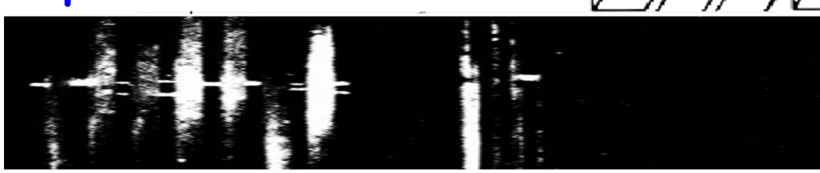
prize 1988



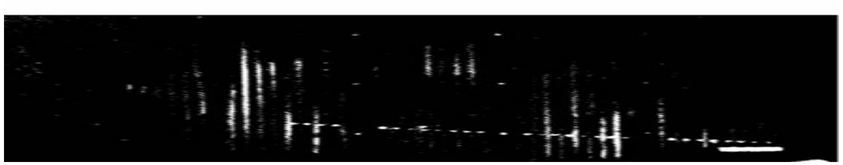


Brookhaven Proton Synchrotron, USA, 1961

10 t spark chamber



ν_μ



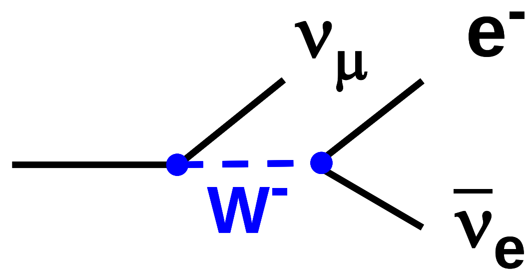
μ

$\nu_\mu \neq \nu_e$

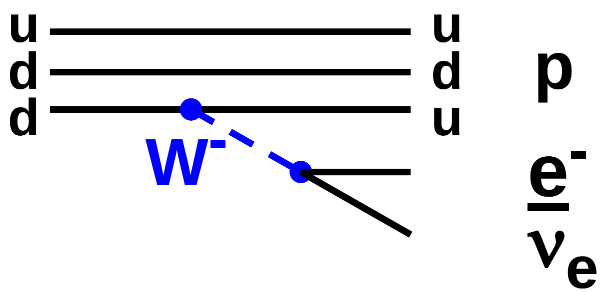
Weak Decays

DECAYS

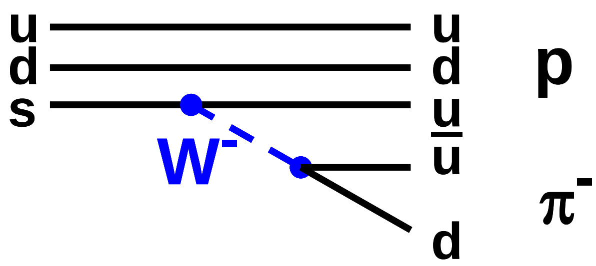
leptonic — μ^- — **μ decay**



semi-leptonic — n — **β decay**



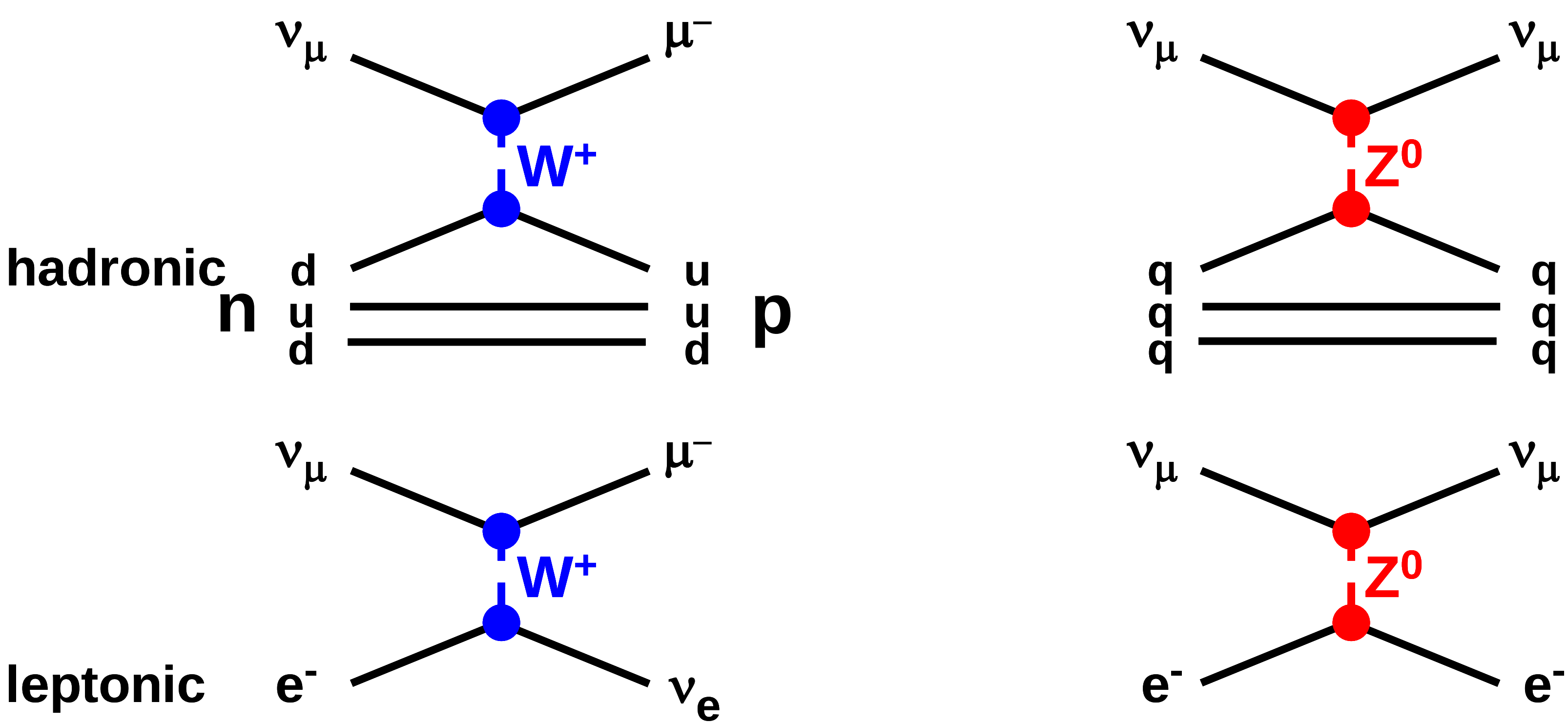
non-leptonic — Λ



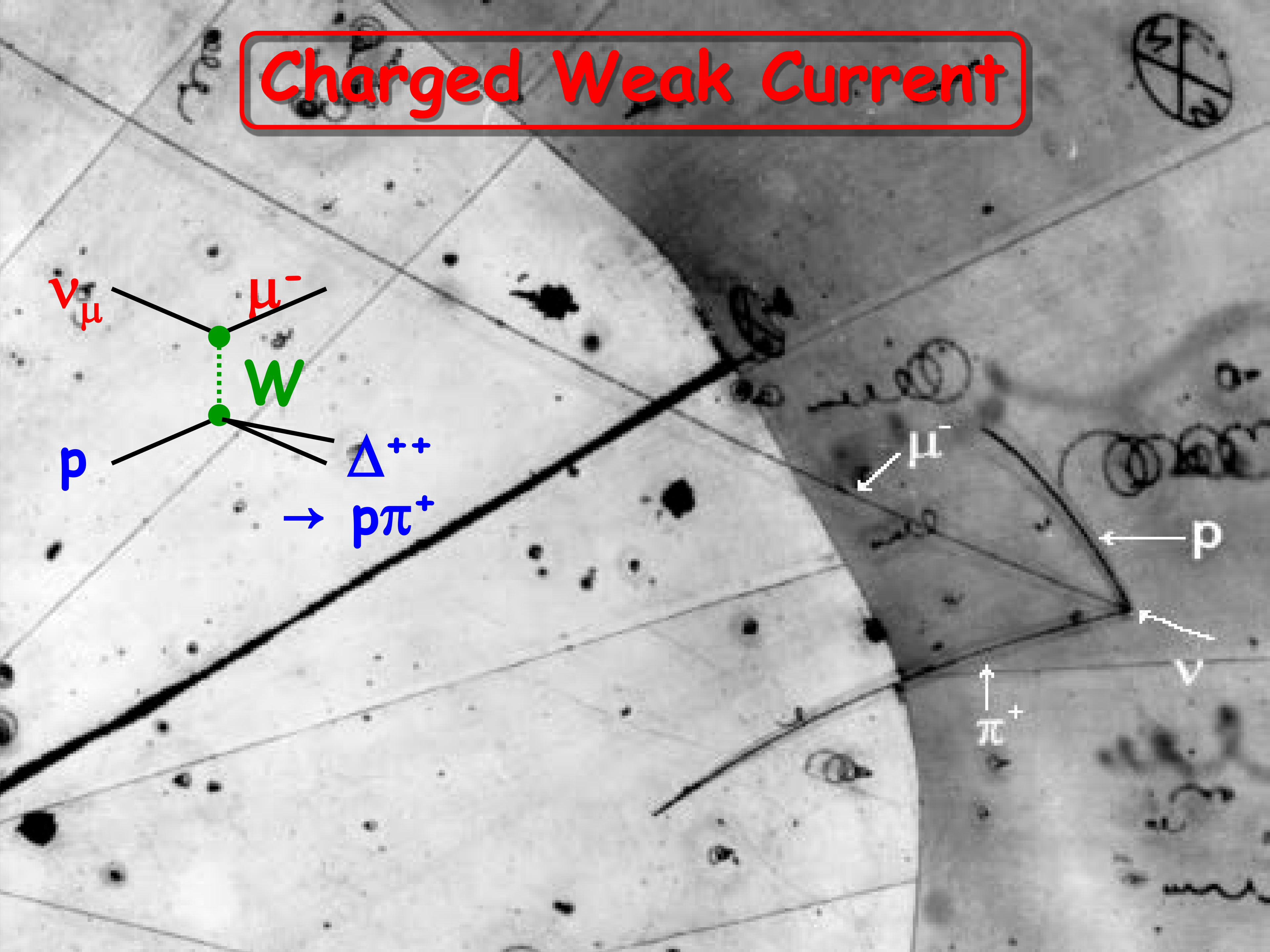
Weak Reactions

current

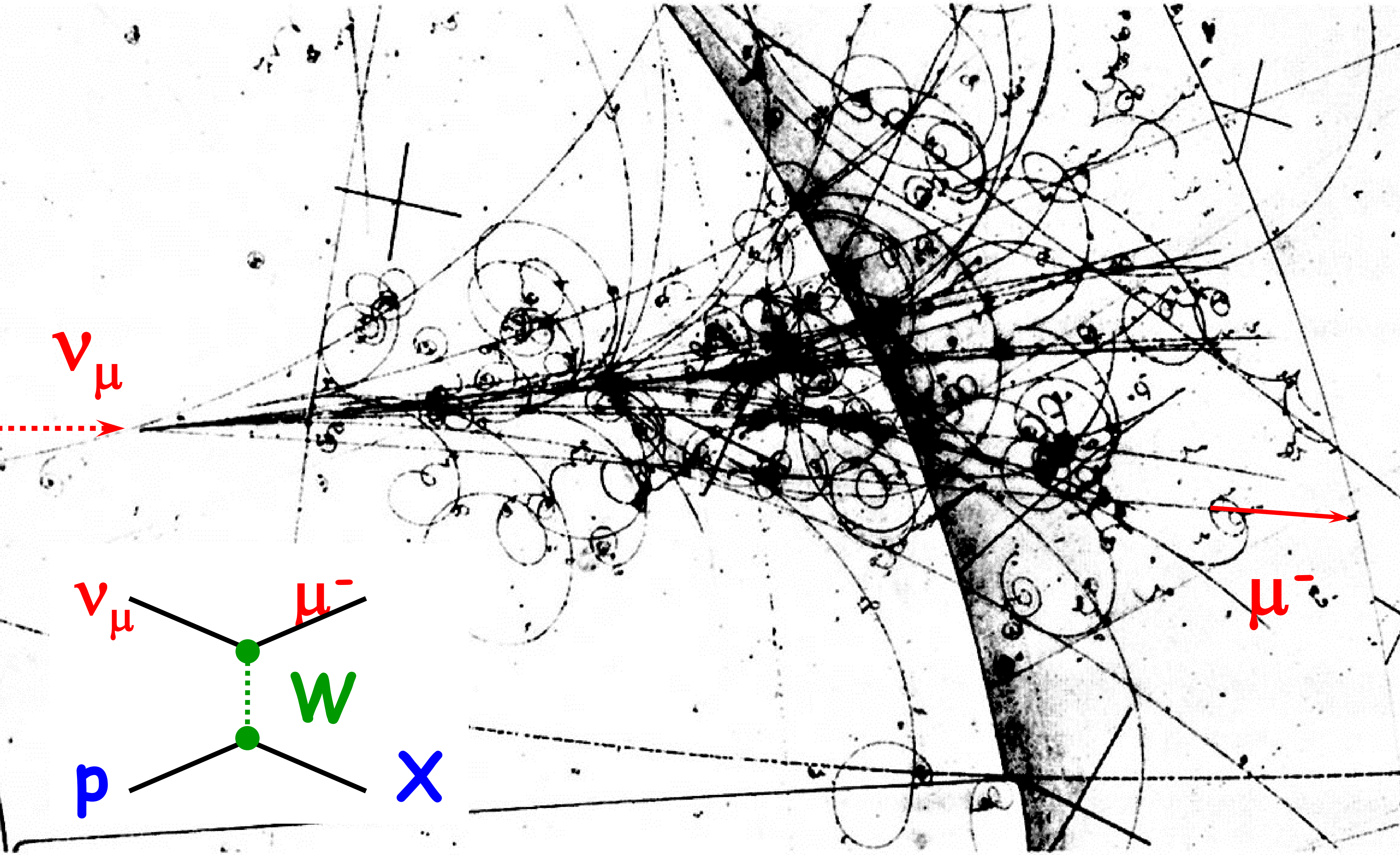
charged **neutral**



Charged Weak Current



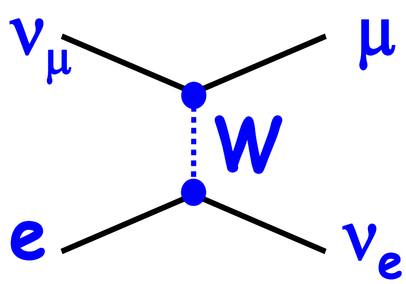
Charged Weak Current



CERN 1984: Big European Bubble Chamber BEBC

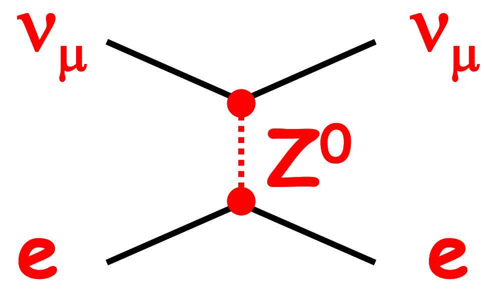
Neutral Weak Current

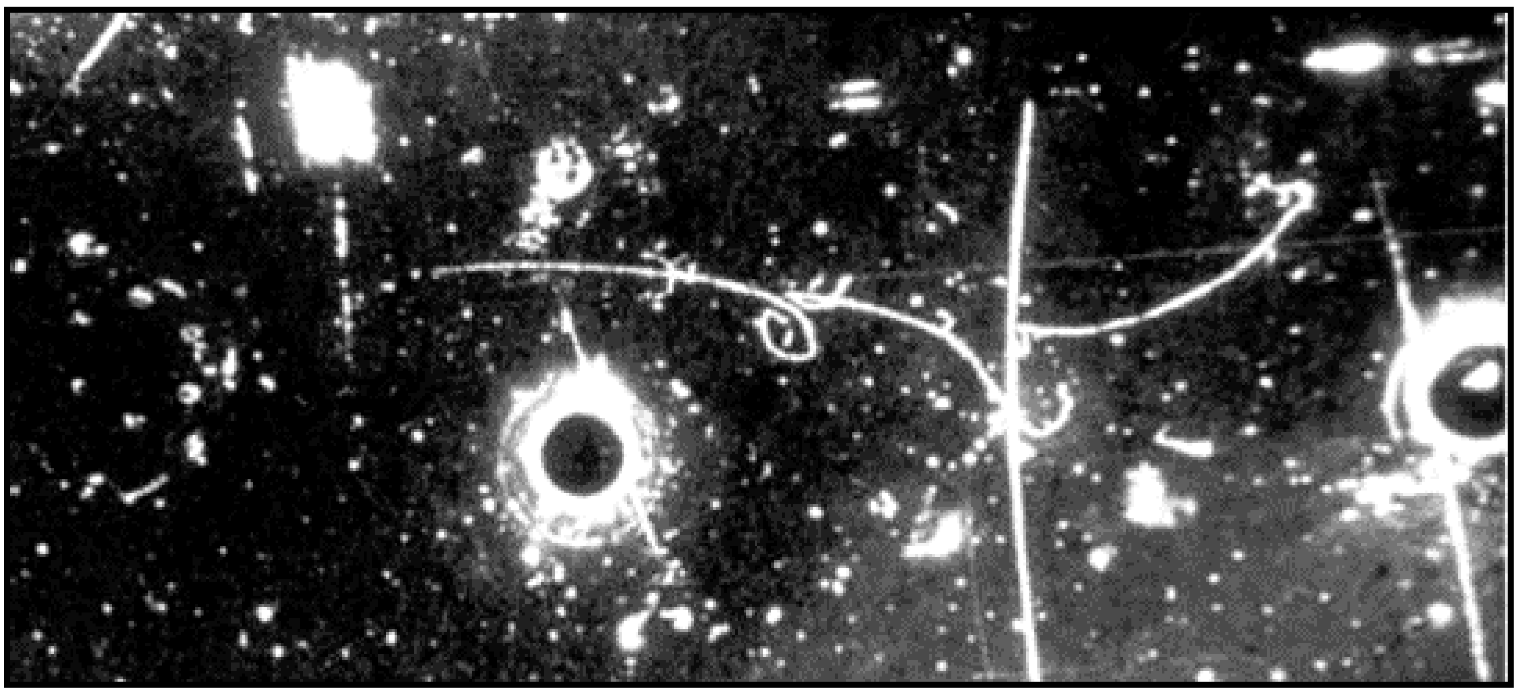
charged current



weak bosons: isotriplet?

neutral current



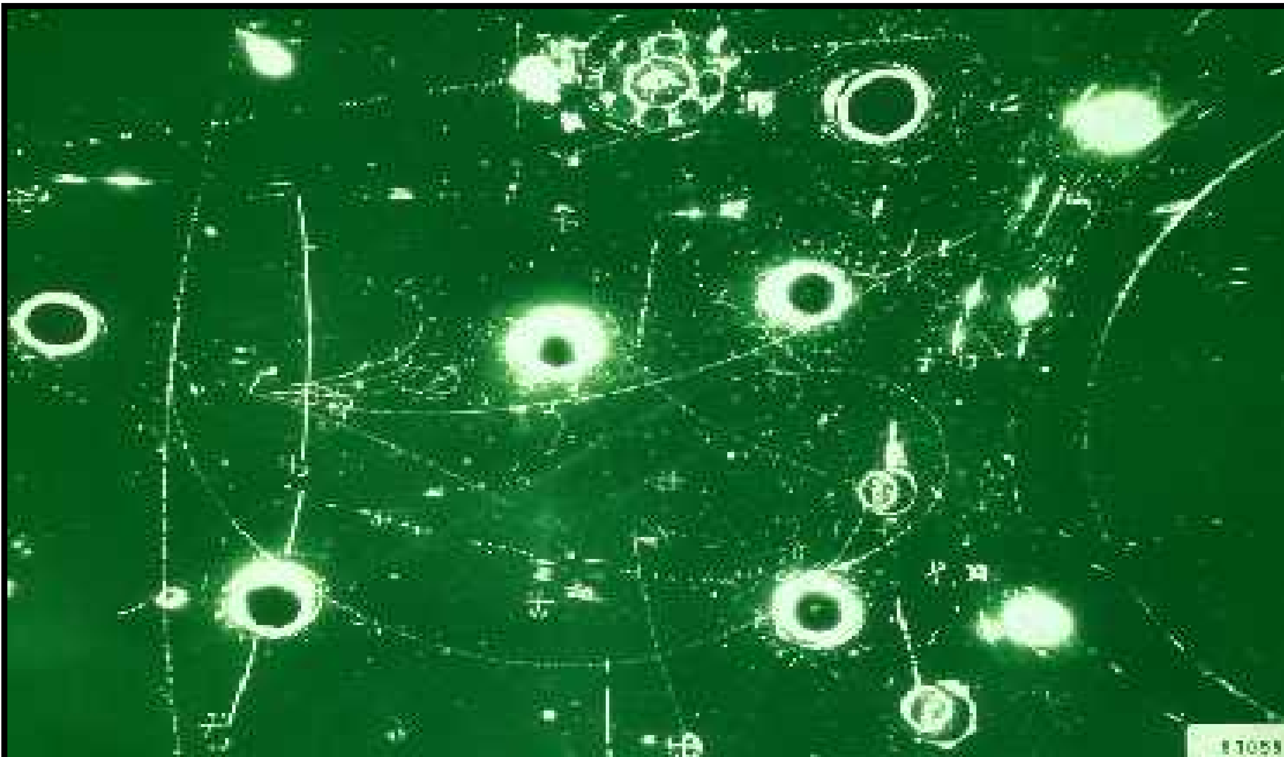


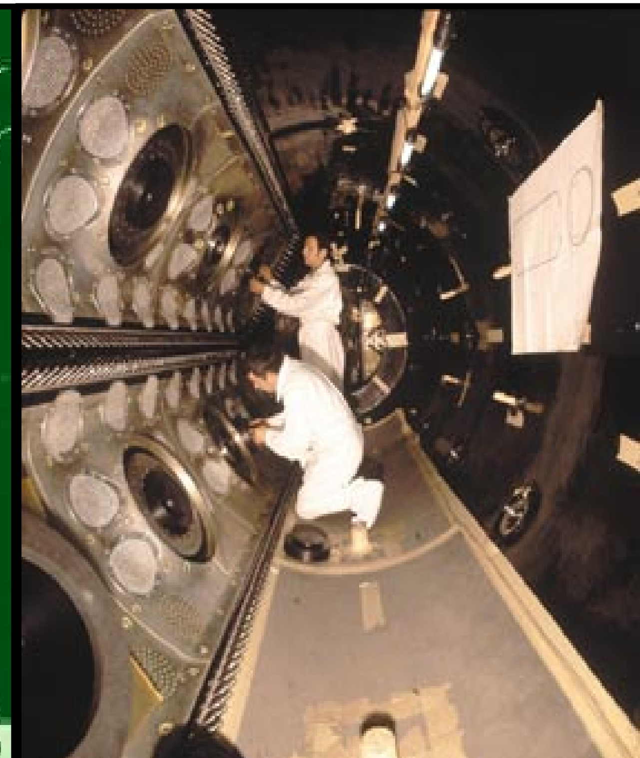
CERN 1973 : Gargamelle Heavy Liquid Bubble Chamber

Neutral Weak Current

$$\nu_\mu N \rightarrow \nu_\mu X$$

CERN 1973: Gargamelle Heavy Liquid Bubble Chamber





Weak Interactions

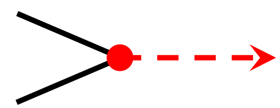
Kinematics

- four-momentum : $p = (E, \mathbf{p})$ $c=1$
- four-momentum^2 : relativistic invariant
- effective mass^2 : $m^2 := p^2 = E^2 - \mathbf{p}^2$

- ultra-relativist.: $m \ll E$ $E = p$
- classic: $p \ll m$ $E = m$

- **s = invariant reaction energy^2**

$\mathbf{p_1}$



$\mathbf{p_2}$

$\mathbf{s = (p_1+p_2)^2}$

omit $\mathbf{p_x=p_y=0}$

- ***Center-of-Mass System :*** e^- ------->< ------- e^+

$(E, \mathbf{p})$ $(E, -\mathbf{p})$

$p_1+p_2 = (2E, 0)$

$s = 4\,E^2$

- **Lab system :** 1 --------> • 2

$(E_1, \mathbf{p_1})$ $(m_2, \mathbf{0})$

$m_{1,2} \ll E_1$

$p_1+p_2 = (E_1+m_2, E_1)$

$s = 2\,m_2 E_1$

target mass effect: $m_p = 2000\,m_e$

Cross Sections

- **cross section:** $\sigma = \pi R^2$

  $[\sigma]$ = barn 1 b = 10^{-24} cm²

  1 mb = 10^{-27} cm²

  1 fb = 10^{-39} cm²

  strong interaction: $\sigma(\pi N) \sim 30$ mb

- **interaction radius:** $R = \sqrt{\sigma/\pi}$

  R (strong) $\sim \sqrt{10^{-30}\,\text{m}^2} \sim 10^{-15}$ m = 1 fm = 1 fermi

- **lifetime:** $\tau = R / c$ = reaction time

  τ (strong) = 1 fm / c = 3×10^{-24} s

- **uncertainty relation:** $\hbar = \Gamma \tau$

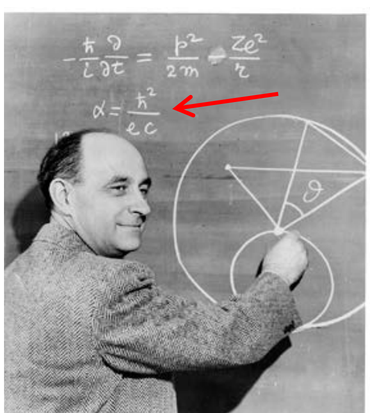
  $\hbar c$ = 200 MeV fm = $\Delta E\, \Delta R$

- **decay width:** $\Gamma = \hbar / \tau = \hbar c / R$

  energy scale $\Gamma = E$

  Γ = 200 MeV fm / R

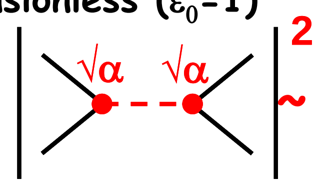
  E (strong) = 200 MeV Γ (strong: Δ, ρ) = 120-150 MeV



- **coupling constant:** $F = \alpha\, \hbar c / r^2$ electric force

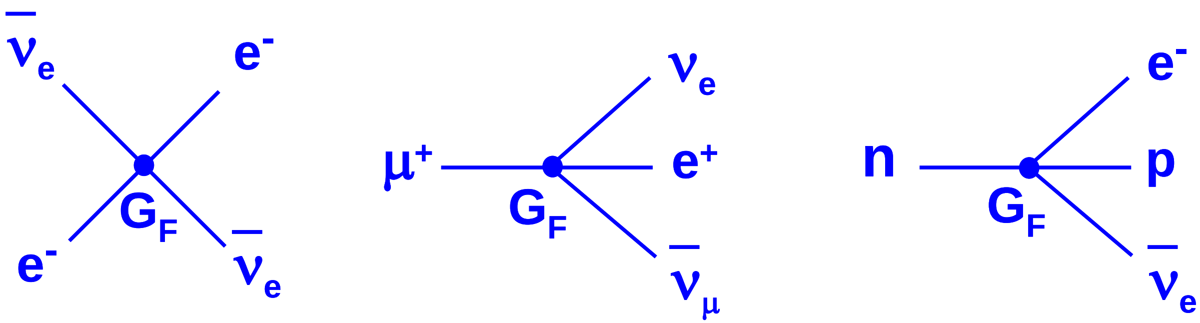
  $\alpha = e^2 / (4\pi\, \hbar c)$ dimensionless (ε_0=1)

$E = \Gamma = \hbar/\tau = \hbar c / R = \hbar c$

$\sigma \sim$  $\sim \alpha^2$

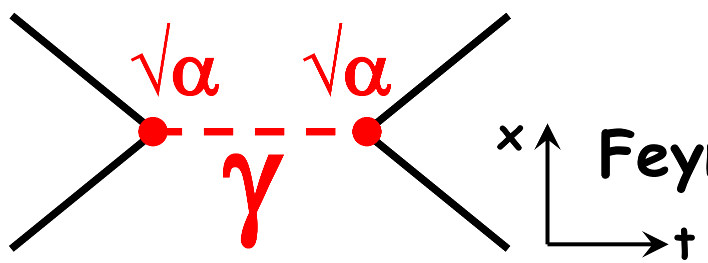
four-fermion theory

E.Fermi, Rome 1933:



four-fermion theory of weak interaction

R.Feynman,
USA 1948:

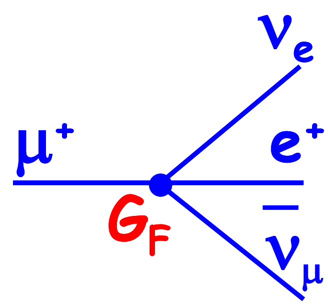


Feynman diagrams

Fermi constant

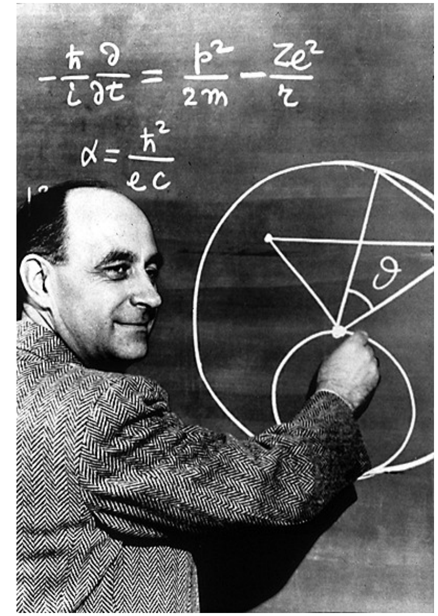
4 Fermi theory of weak interaction with coupling constant

G_F = 1.1663788 (7) × 10^{-5} GeV^{-2}



determined from muon lifetime

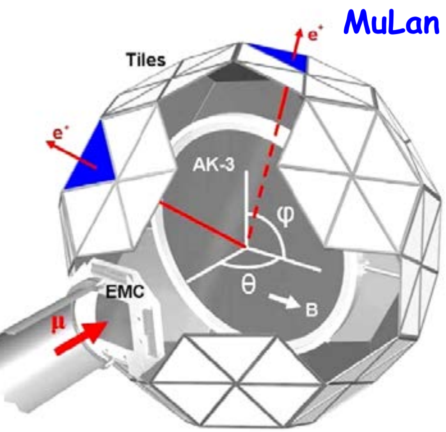
$\tau_\mu = 192\pi^3/(G_F^2 m_\mu^5)\ (1+\delta_{kin})\ (1+\delta_{weak})\ (1+\delta_{QED})$

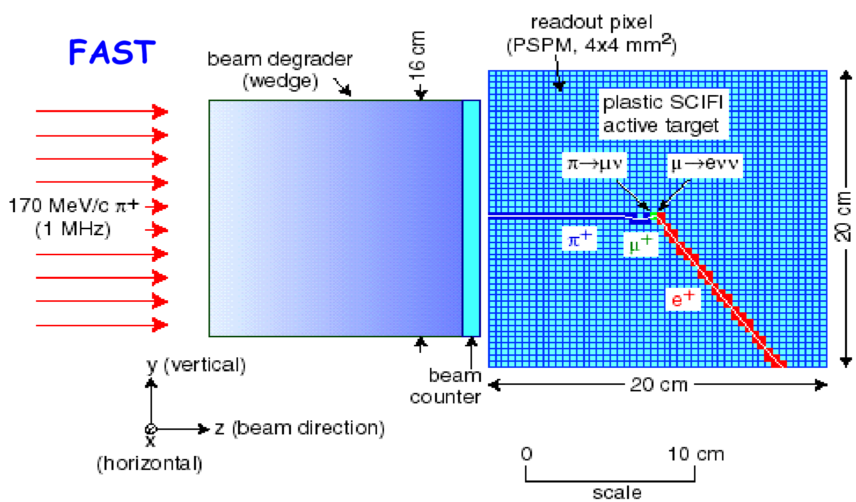


E. Fermi

Nobel  prize

1938





$>10^{12}$ μ decays

τ_μ = 2 196 980 (2) ps

get G_F to $<10^{-6}$

FAST, MuLan @ PSI

MuLan: arXiv:1211.0960
FAST: arXiv:0707.3904

Weak interaction

- **QED:** $F = \alpha \hbar c / r^2$ electric force ($\varepsilon_0 = 1$)

coupling constant $\alpha = e^2 / (4\pi \hbar c) = 1/137$ dimensionless !

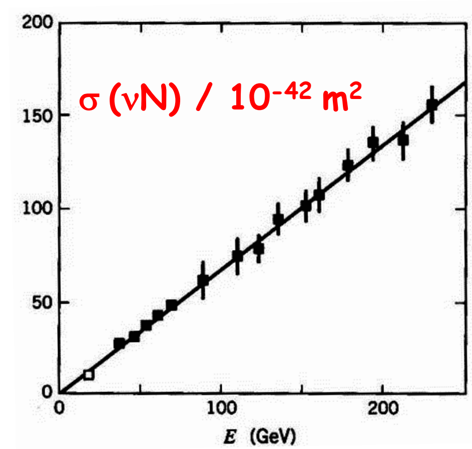
$\sigma(e^+e^- \to \mu^+\mu^-) = 4\pi/3 \ \alpha^2/s \approx 80 \text{ nb} / (s/\text{GeV}^2)$

$s \to \infty \Rightarrow \sigma \to 0$ charge point like !

$[\alpha^2] = [\sigma s] = [l^2 E^2] = [\hbar c]^2 = 1$ dimensionless ($\hbar c$ = 200 MeV fm)

- **weak force:**

$\sigma(\nu_\mu e^- \to \nu_e \mu^-) = G_F^2 \, s / \pi$



$s \to \infty \Rightarrow \sigma \to \infty$ Unitarity violated !

$\hbar^2 c^2 = 0.4 \text{ GeV}^2 \text{ mb}$

$[G_F^2] = [\sigma/s] = [l^2/E^2] = [\hbar^2 c^2/E^4] \Rightarrow$

$[G_F] = [E^{-2}] = \text{GeV}^{-2}$???

weak coupling constant G_F contains energy scale !

Weak Interaction

$$\sigma(\nu_\mu e^- \rightarrow \nu_e \mu^-) = G_F^2\, s / \pi$$

$$G_F = 1.2 \times 10^{-5}\ \mathrm{GeV}^{-2}$$

$s \approx 2\, m_e E_\nu$

$\sigma = 9.5 \times 10^{-11}\ \mathrm{GeV}^{-2}\ [m_e/\mathrm{GeV}]\ [E_\nu/\mathrm{GeV}]$

$\hbar c = 1 = 0.2\ \mathrm{GeV\ fm}$

$(\hbar c)^2 = 1 = 0.04\ \mathrm{GeV}^2\ \mathrm{fm}^2 = 0.4\ \mathrm{mb\ GeV}^2$

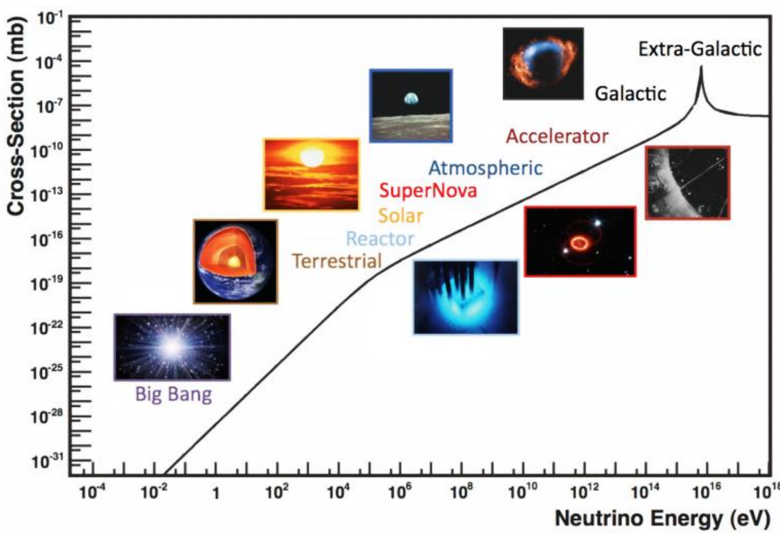
$\sigma = 3.8 \times 10^{-11}\ \mathrm{mb}\ [m_e/\mathrm{GeV}][E_\nu/\mathrm{GeV}] = 10^{-16}\ \sigma$ (strong: $\pi p \rightarrow \Delta$)

$\sigma = 3.8 \times 10^{-12}\ \mathrm{fm}^2\ [m_e/\mathrm{GeV}][E_\nu/\mathrm{GeV}]$

$\sigma = 3.8 \times 10^{-42}\ \mathrm{m}^2\ [m_e/\mathrm{GeV}][E_\nu/\mathrm{GeV}]$

σ extremely weak !

$m_N/m_e = 2.000$, $m_A/m_N > 100$ =>
target mass effect !



neutrino interactions

Fermi constant very small:

mean free path of 1 MeV solar neutrino in Earth :

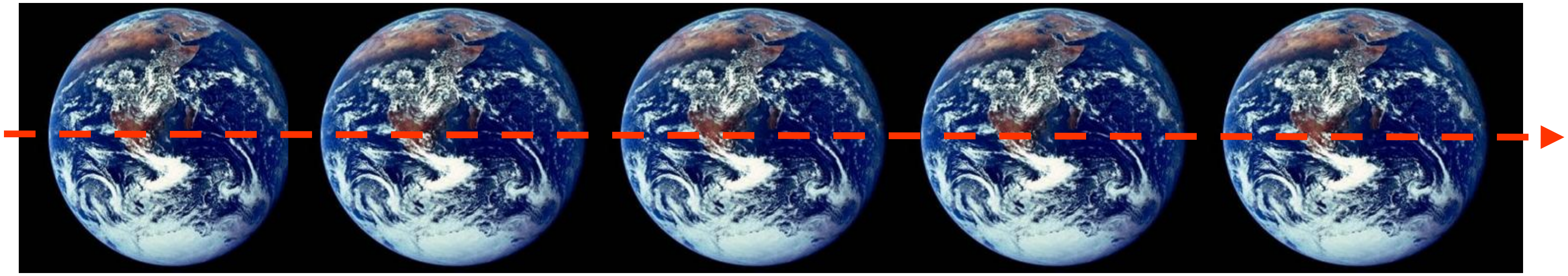
σ = 3.8 x 10^{-42} m^2 $[m_A/GeV][E_\nu/GeV]$

$1/L = \sigma \rho / m_N$

$\rho / m_N = 5.5\ g/cm^3 / 1.67\ 10^{-24}\ g = 3.3\ 10^{24} /cm^3$

$1/L = 3.3\ 10^{24}/cm^3\ 2\ 10^{-44}\ cm^2 = 6.6\ 10^{-20} /cm$

$L = 1.5\ 10^{14}$ km = $2\ 10^{10}\ R_{Earth}$ ~ 10 light years:

ν 

10 billion Earths

only 1 solar neutrino/person/human life reacts !

Weak Interaction

$[G_F] = GeV^{-2}$

Which energy scale hidden in G_F ?

assume

point like electro-weak coupling with α_W:

$$G_F^2 \, s / \pi = \sigma = \alpha_W^2 \, \pi / s$$

$$s^2 = \alpha_W^2 \, \pi^2 / G_F^2$$

electro-weak energy scale:

$\sqrt{s} \sim \sqrt{G_F^{-1}} \sim \sqrt{10^5} \text{ GeV} \sim 300 \text{ GeV}$

collapse of Fermi theory

massive exchange boson W

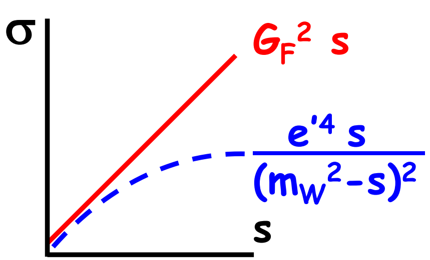
Weak Interaction

$G_F \rightarrow e'^2 / (m_W^2 - s)$

e' ... weak charge, dimensionless
massive W boson, correct s dependence.

- $s \rightarrow 0$: $e'^2 = m_W^2 G_F = e^2 = 4\pi\alpha \sim 0.1$
  weak ~ electric force !
  $m_W^2 = 4\pi\alpha / G_F$ $m_W \sim 90$ GeV

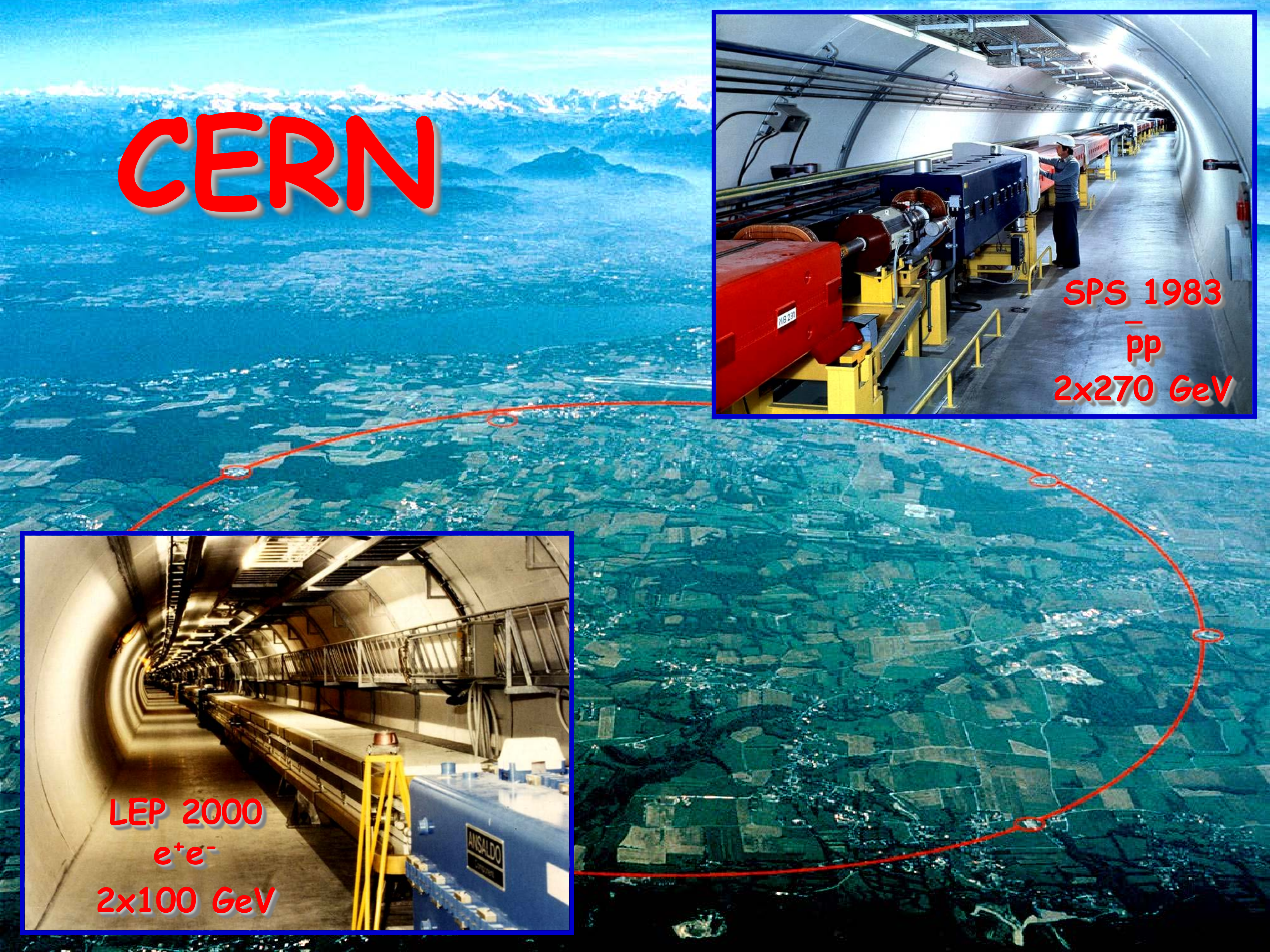
- $s \gg m_W^2$: $\sigma \sim e'^4 / s$ scatter on pointlike charge



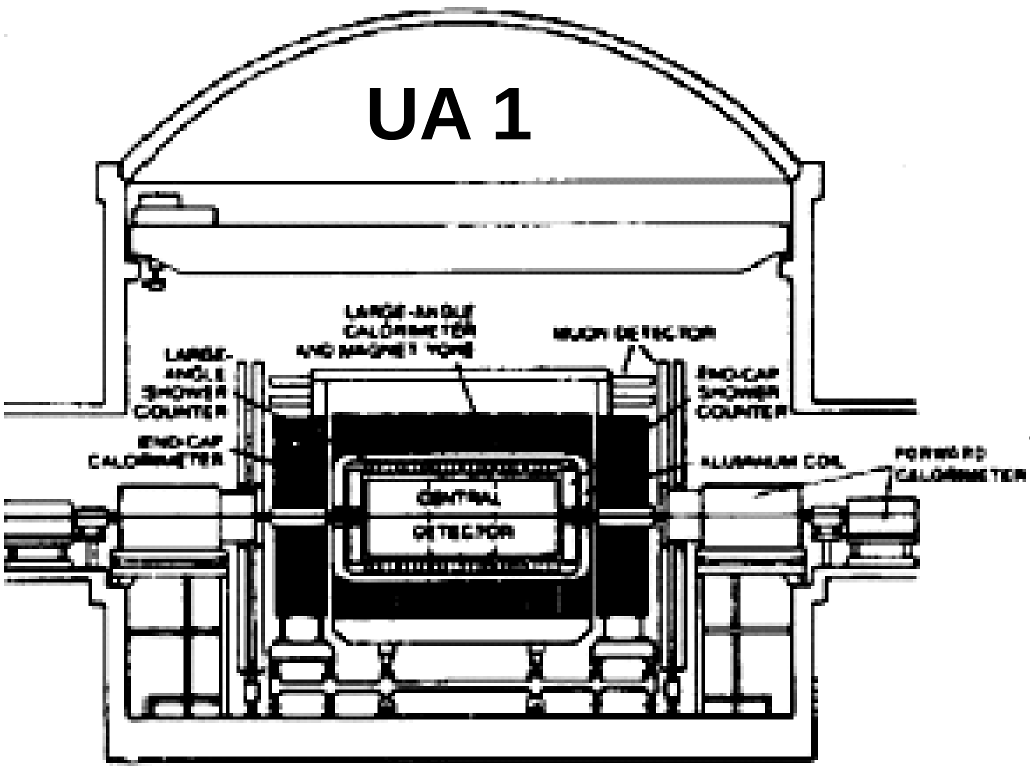
$s \rightarrow \infty$ => $\sigma \rightarrow \infty$ unitarity violated !

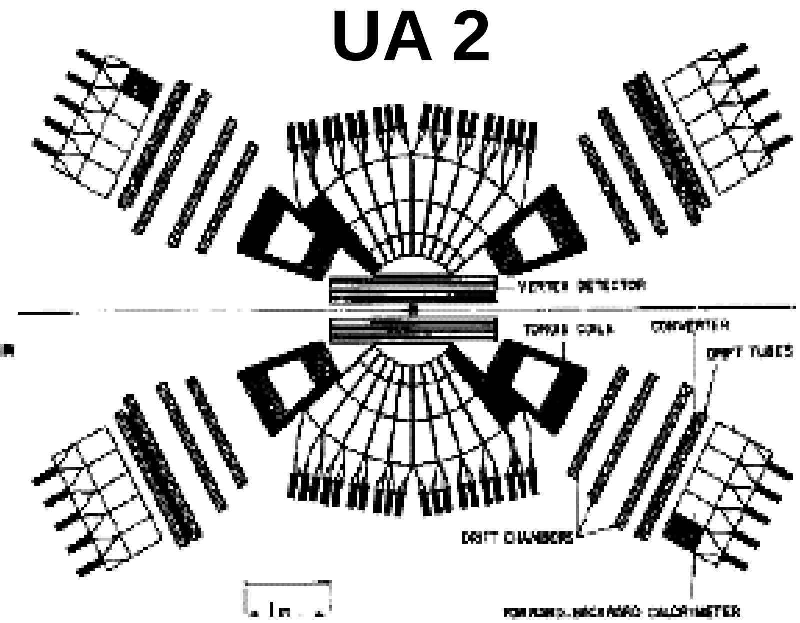
weak charge, dimensionless
massive W boson
correct s dependence

~1970: find $W^{\pm}+Z^0$ bosons !


CERN
SPS 1983
$\bar{p}p$
2x270 GeV
LEP 2000
e^+e^-
2x100 GeV

W+Z Discovery





Expts. UA1+UA2 1983

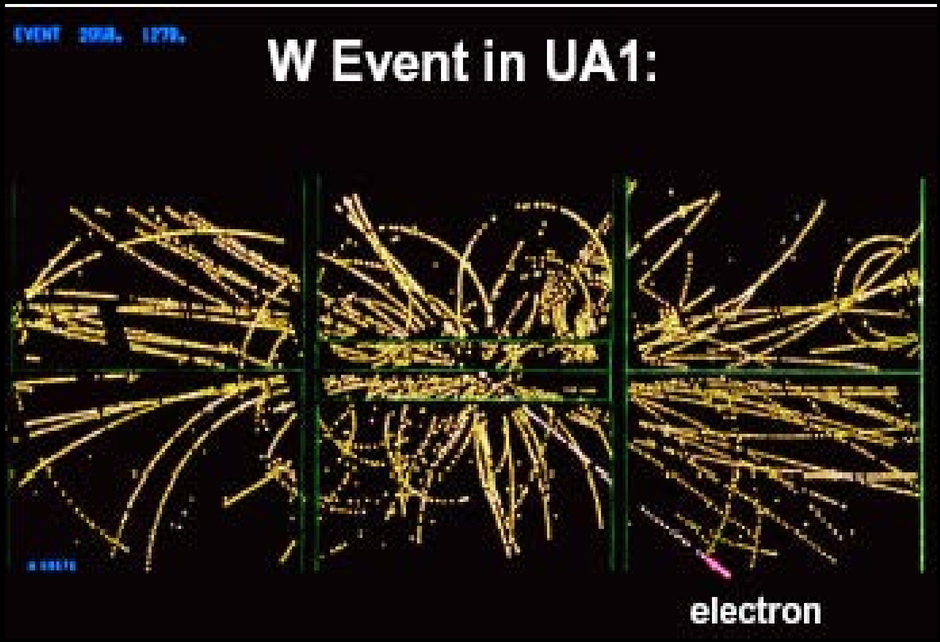
C. Rubbia

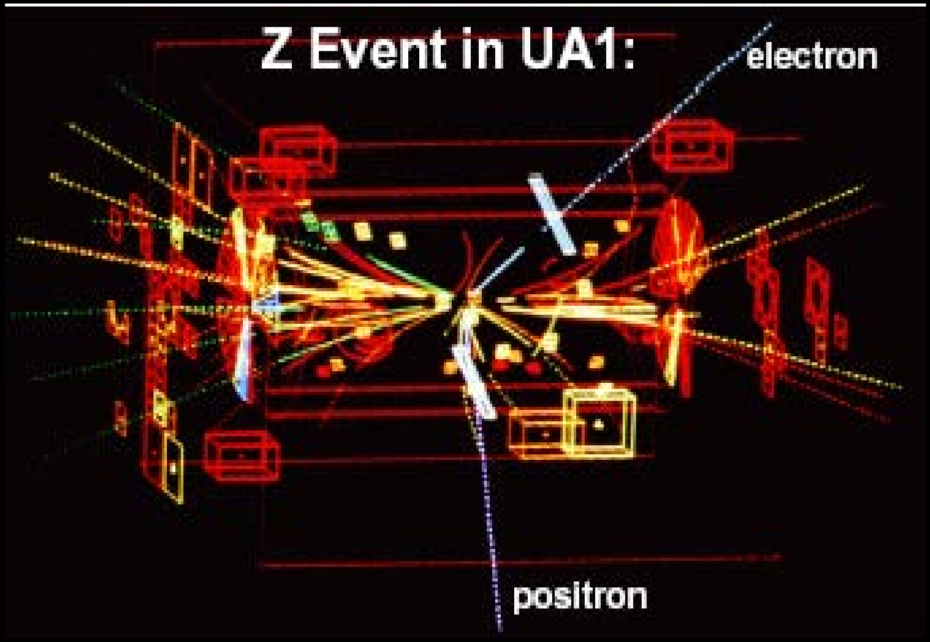
SPS p $\bar{p}$ collider at CERN

S. van der Meer

Nobel prize 1984

W+Z Discovery





$u \bar{d} \to W^+ \to e^+ \nu_e$

$q \bar{q} \to Z^0 \to e^+ e^-$

Expts. UA1+UA2 1983

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