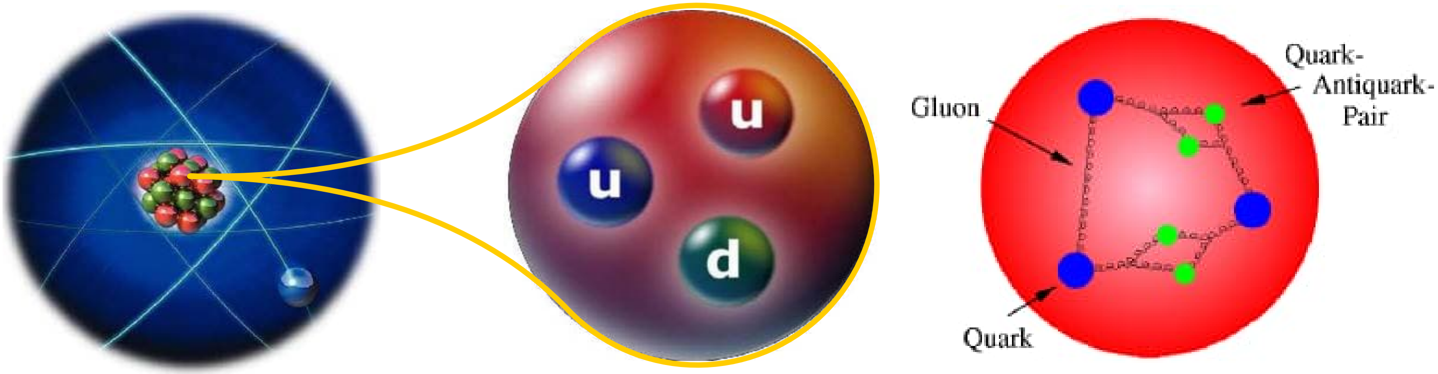
Particle Physics

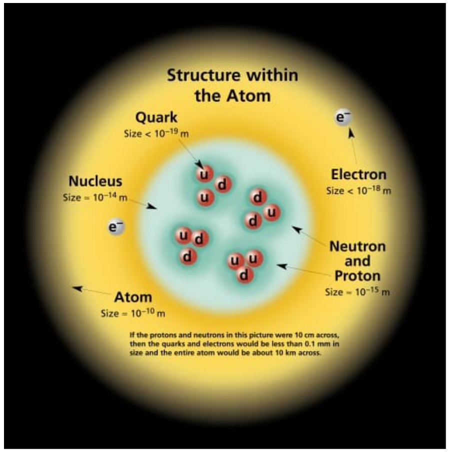


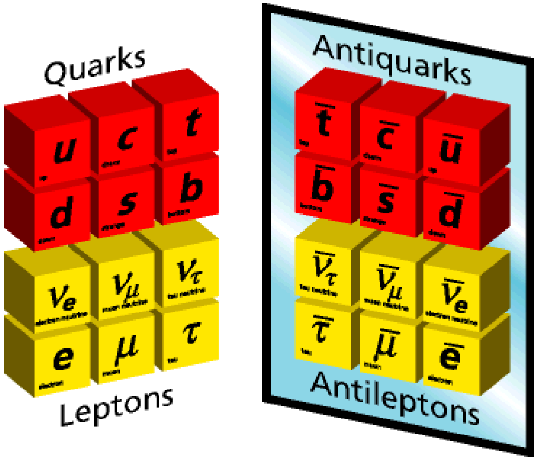
The proton does not only consist of three quarks ***(blue)*** being held together by gluons ***(springs)***, but is a sizzling place of gluons and pairs of quarks and antiquarks ***(green)*** interacting with each other.

Particle physics is a branch of physics that studies the elementary constituents of matter and radiation, and the interactions between them. It is also called "high energy physics", because many elementary particles do not occur under normal circumstances in nature, but can be created and detected during energetic collisions of other particles, as is done in particle accelerators

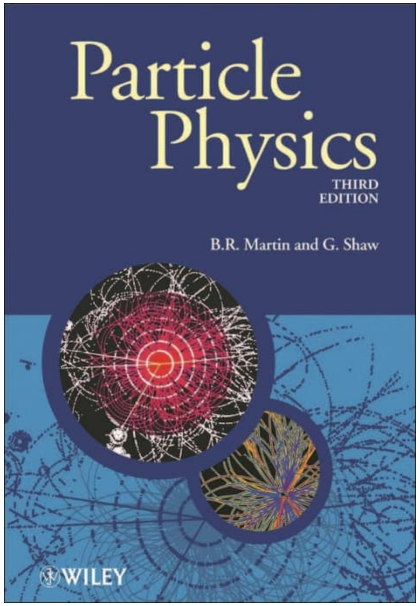
Tentative outline of Particle Physics

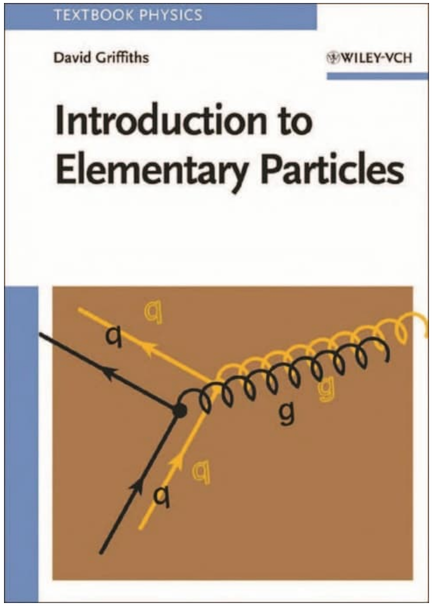
- **Introduction**
  - 100 years of particle physics
- **Basic Concepts**
  - Forces of nature
  - Standard model chart
  - Lepton and Baryon numbers
  - Units and dimensions
  - Cross section and decay rates
- **Feynman Diagrams**
  - exchange of photons
  - exchange of massive bosons
  - Yukawa potential
  - Weak, electromagnetic, strong interaction
- **Leptons**
  - Weak interaction (beta decay)
  - Electron, muon, tau
  - Tau decay
  - Lepton conservation
- **Quarks**
  - Example of baryons and meson
  - Quark number conservation
  - Isospin
  - Color a new quantum number
- **Summary & Open Questions**
- **Beyond the Standard Model**





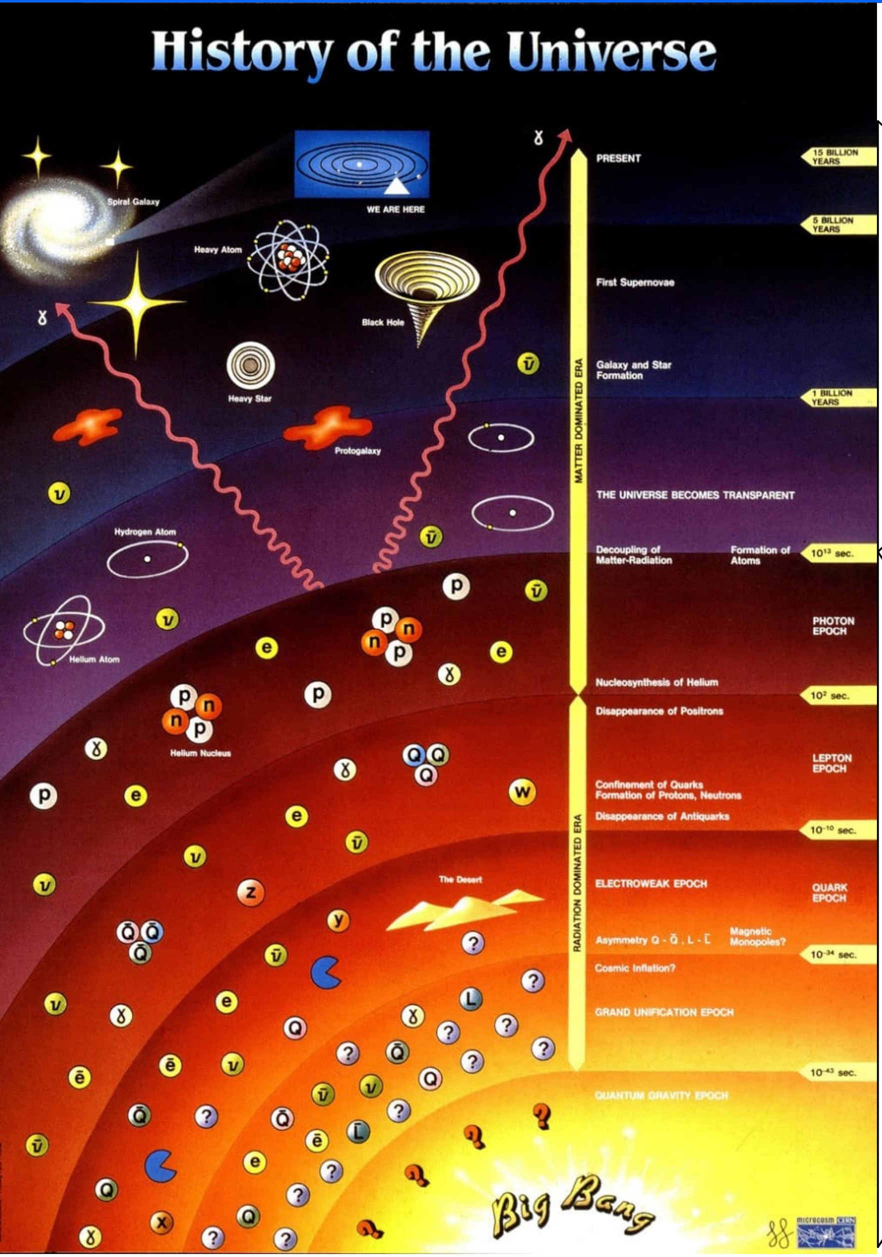
Literature





- Recommended Textbook

Particle Physics

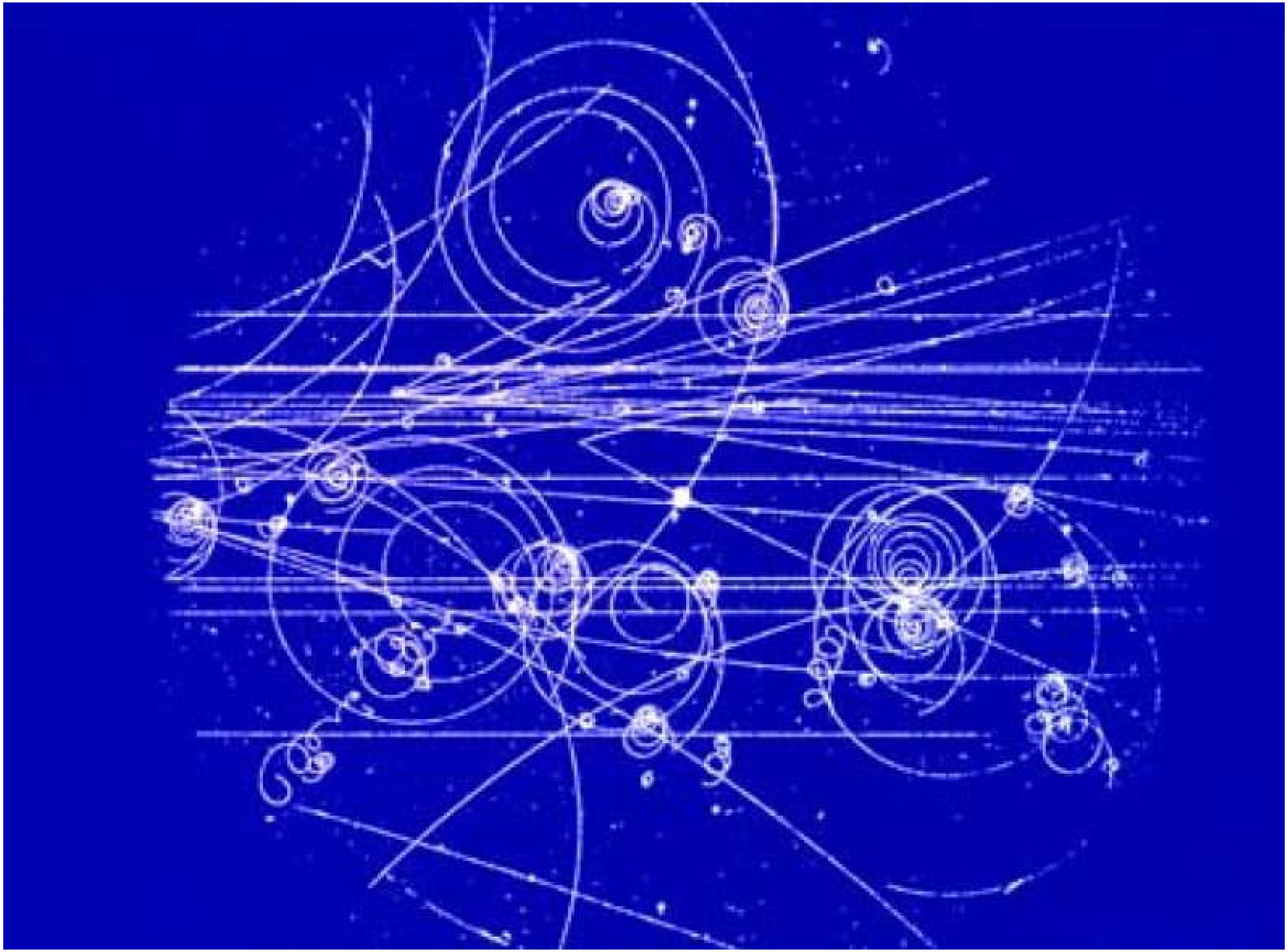


era of gravitation

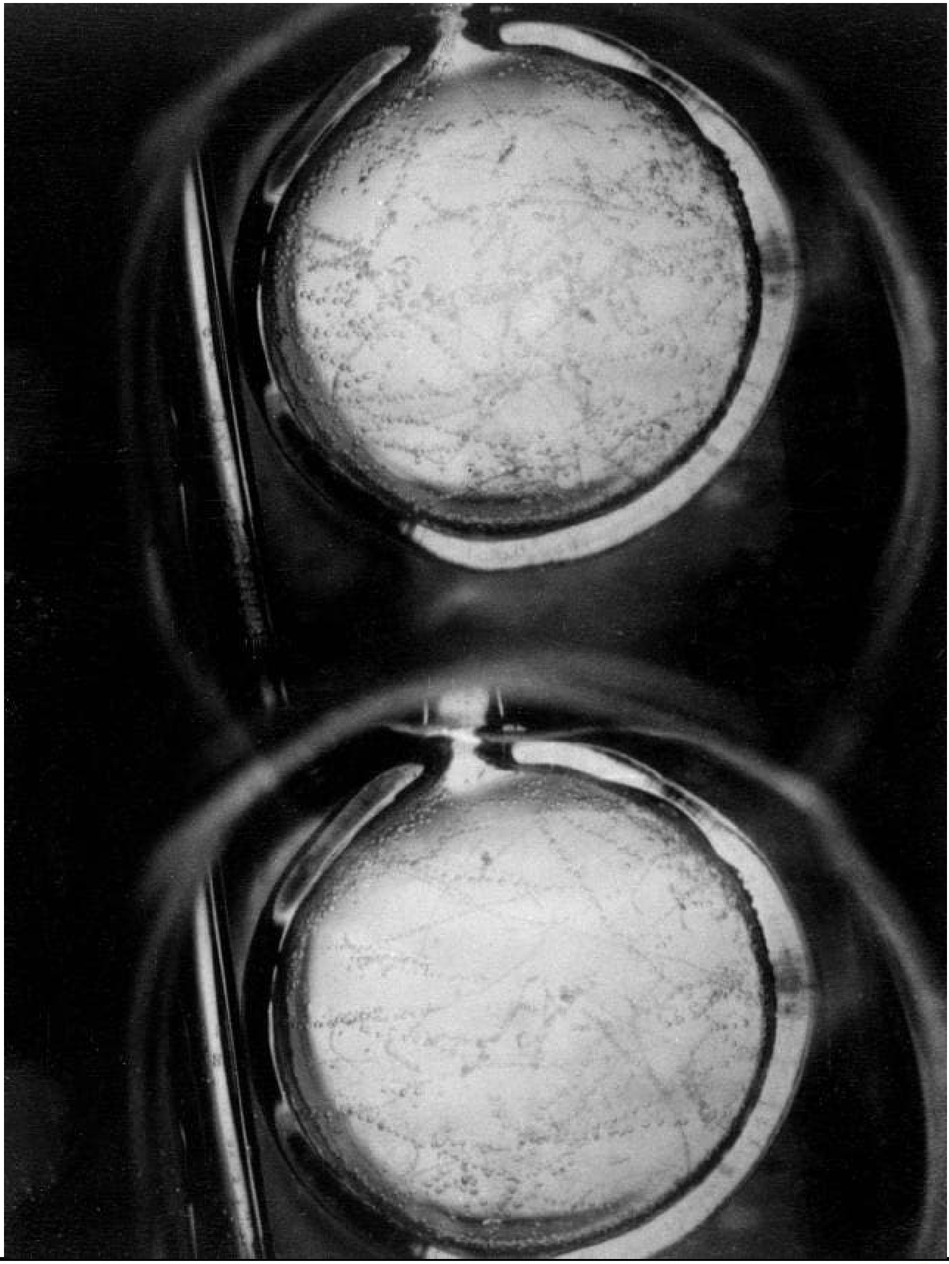
$10^{13}\ s\ \approx$ 300 000 years

era of particle physics

100 years of particle physics



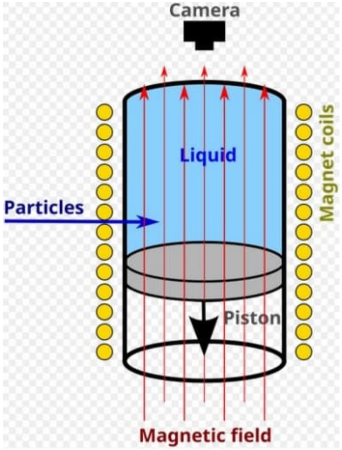
Bubble chamber



How does a bubble chamber work:

- It is filled with a liquid under pressure (hydrogen)
- Particles ionize the liquid along their passage
- When pressure drops, liquid boils preferentially along the ionization trails

Donald Glaser

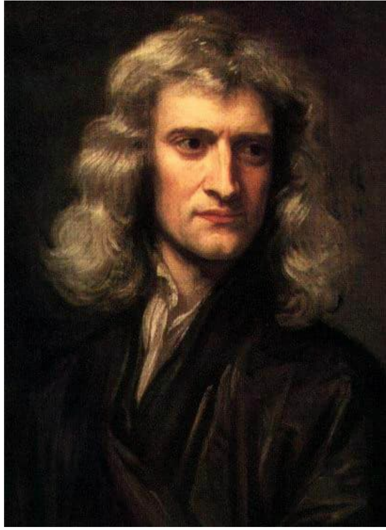


Corpuscular Theory of Light

Light consist out of particles (Newton)

Light is a wave (Huygens)

- Mainly because of Newton’s prestige, the corpuscle theory was widely accepted (more than 100 years)
- Failing to describe interference, diffraction, and polarization (e.g. Fresnel) corpuscle theory was abandoned for Huygens wave theory
- Wave theory strongly supported by Maxwell equations and by H. Hertz experiments
- Until in the early 20th century …



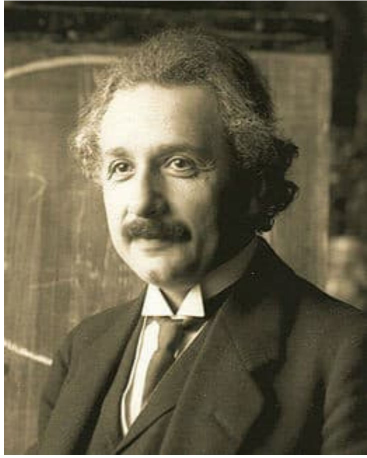
Isaac Newton
1643-1727

Christiaan Huygens
1629-1695

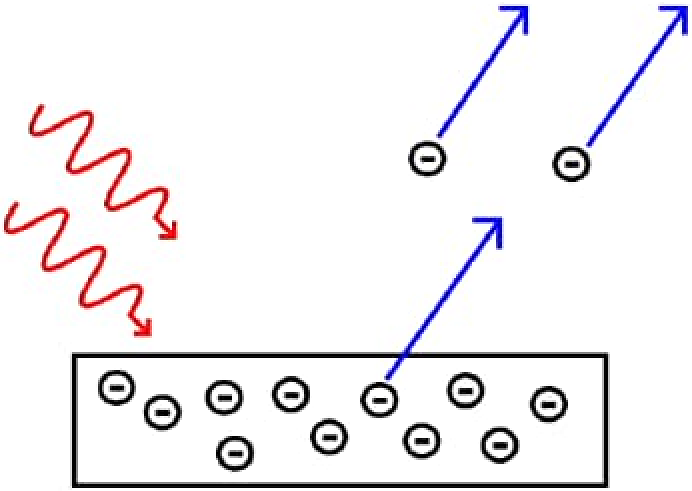
Photoelectric Effect

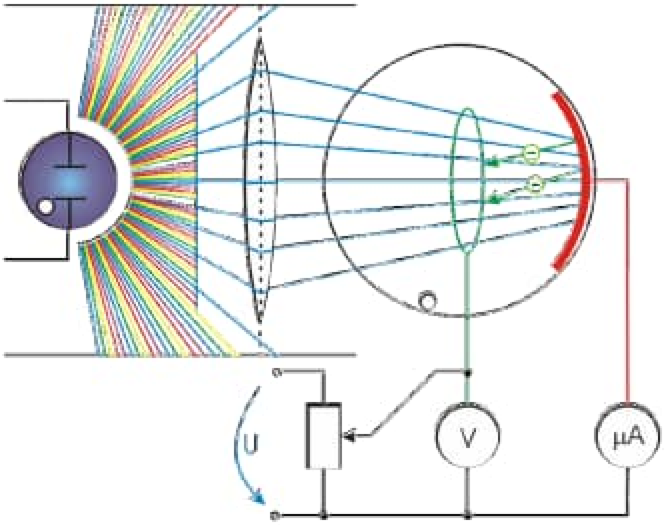
- **Observation:** 1836 Becquerel
  Metal absorbs light and emits electrons →
  Maximum energy of electrons independent on intensity (number of photons)

- **Interpretation:** 1905 Einstein (Nobel prize 1921)
  Light consists of particles (photons) with quantized energy

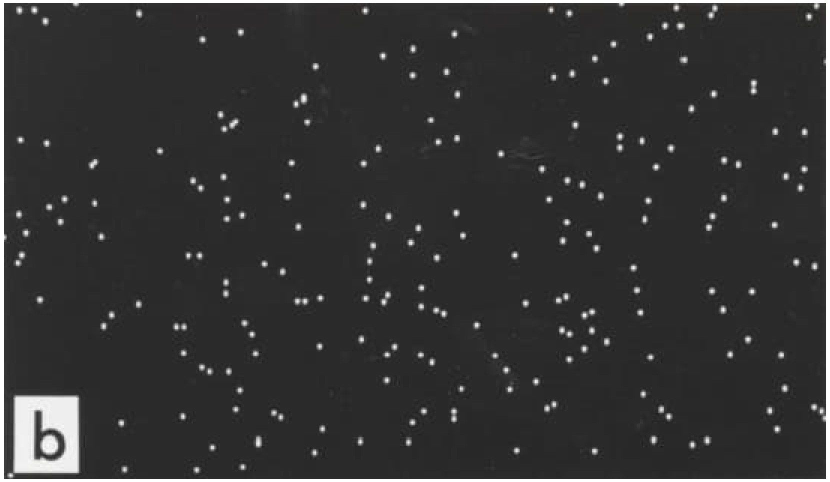


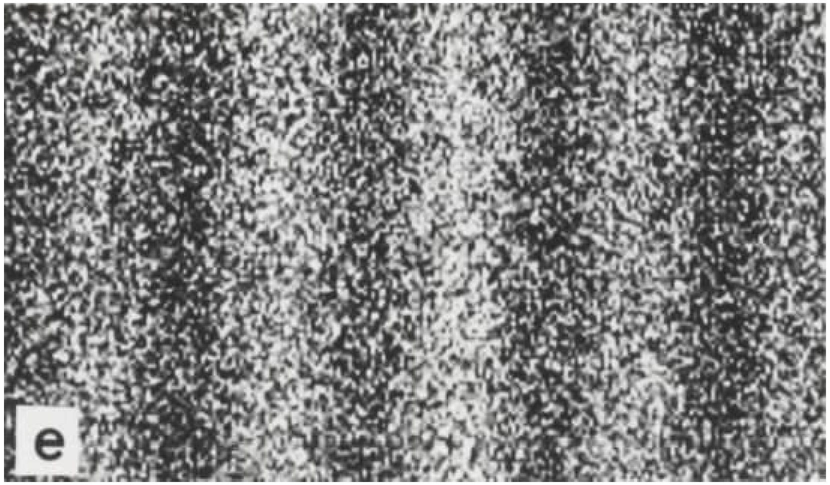
Albert Einstein
1879-1955

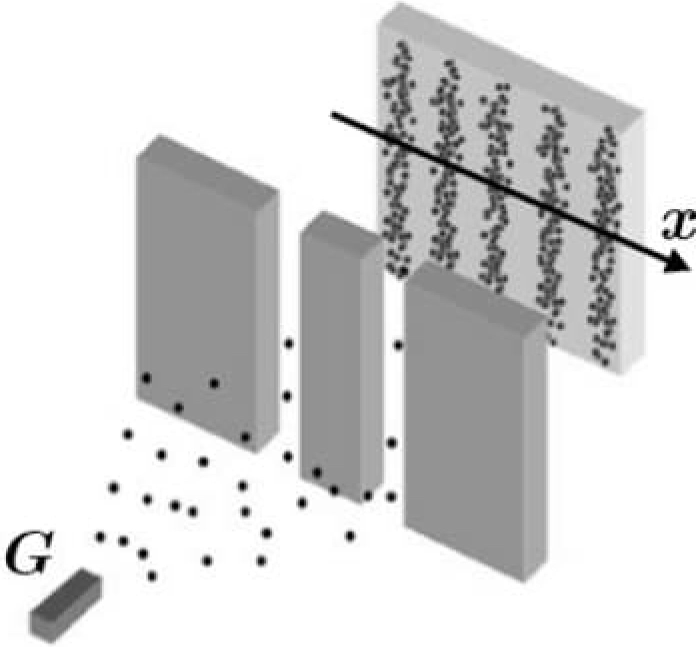




Double Slit with Electrons







Electron (particles) have wavelength

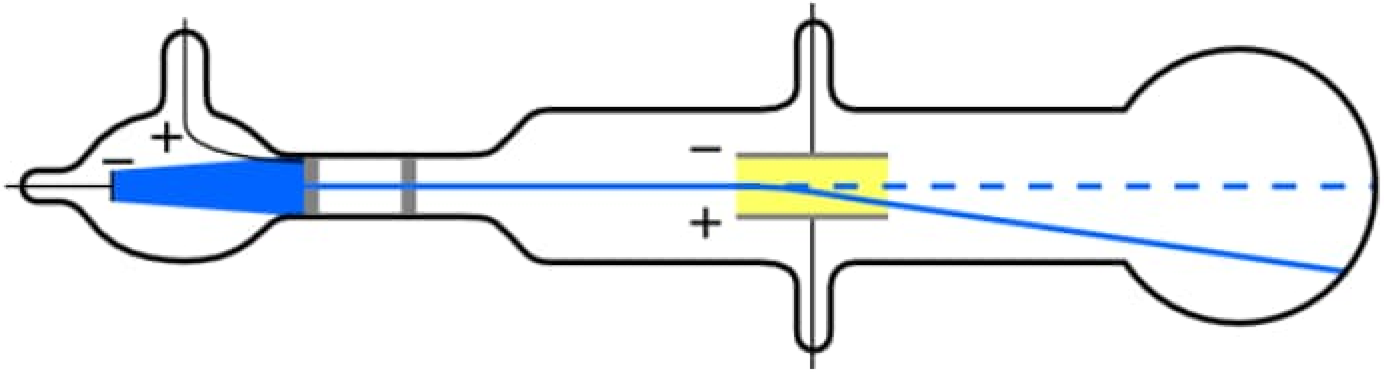
De Broglie wavelength:

$$\lambda = \frac{h}{p} = \frac{Planck\ constant}{momentum\ (= mass\ \cdot velocity)}$$

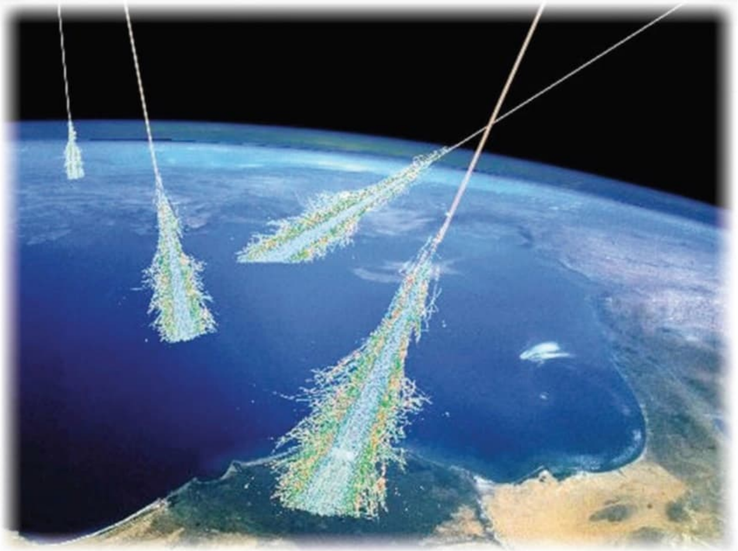
The Electron

- **Observation:** 1897 (Nobel Prize 1906)
  - Constituents of cathode rays deflected by electric field
  - Constituents of cathode rays deflected by magnetic field + heating of thermal junction → first mass/charge ratio
  - Higher precision of mass/charge from comparing deflection by electric and magnetic fields

Joseph J. Thomson
1856-1940

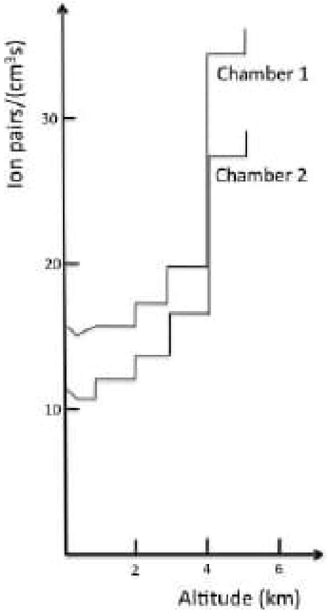


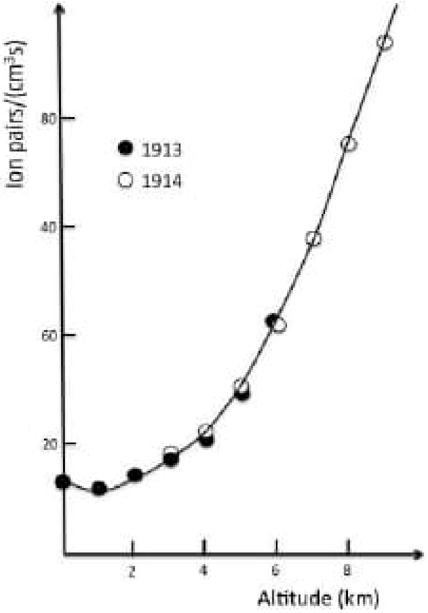
Ionization Measurements



Victor Hess (1912)

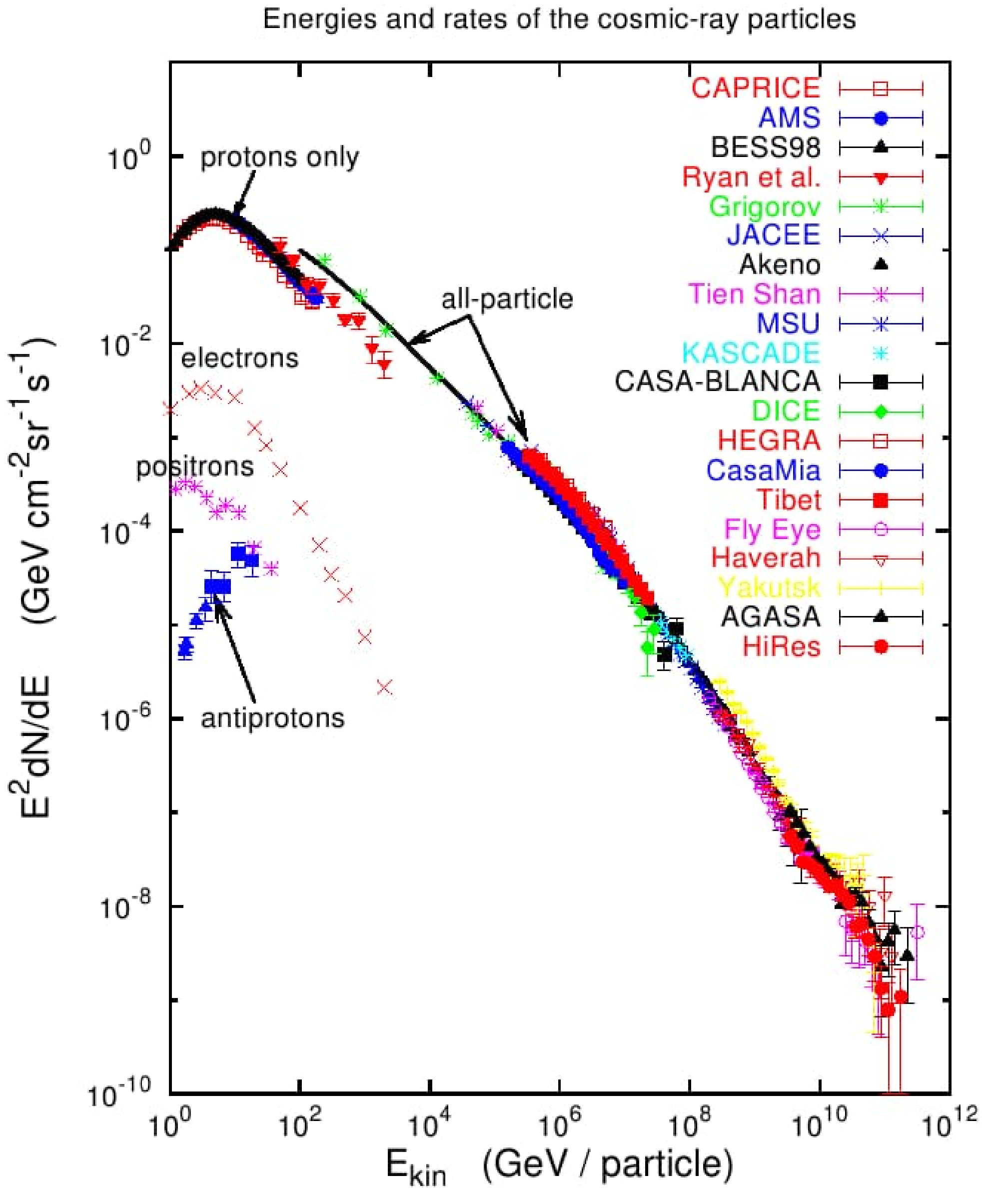
discovery of cosmic showers



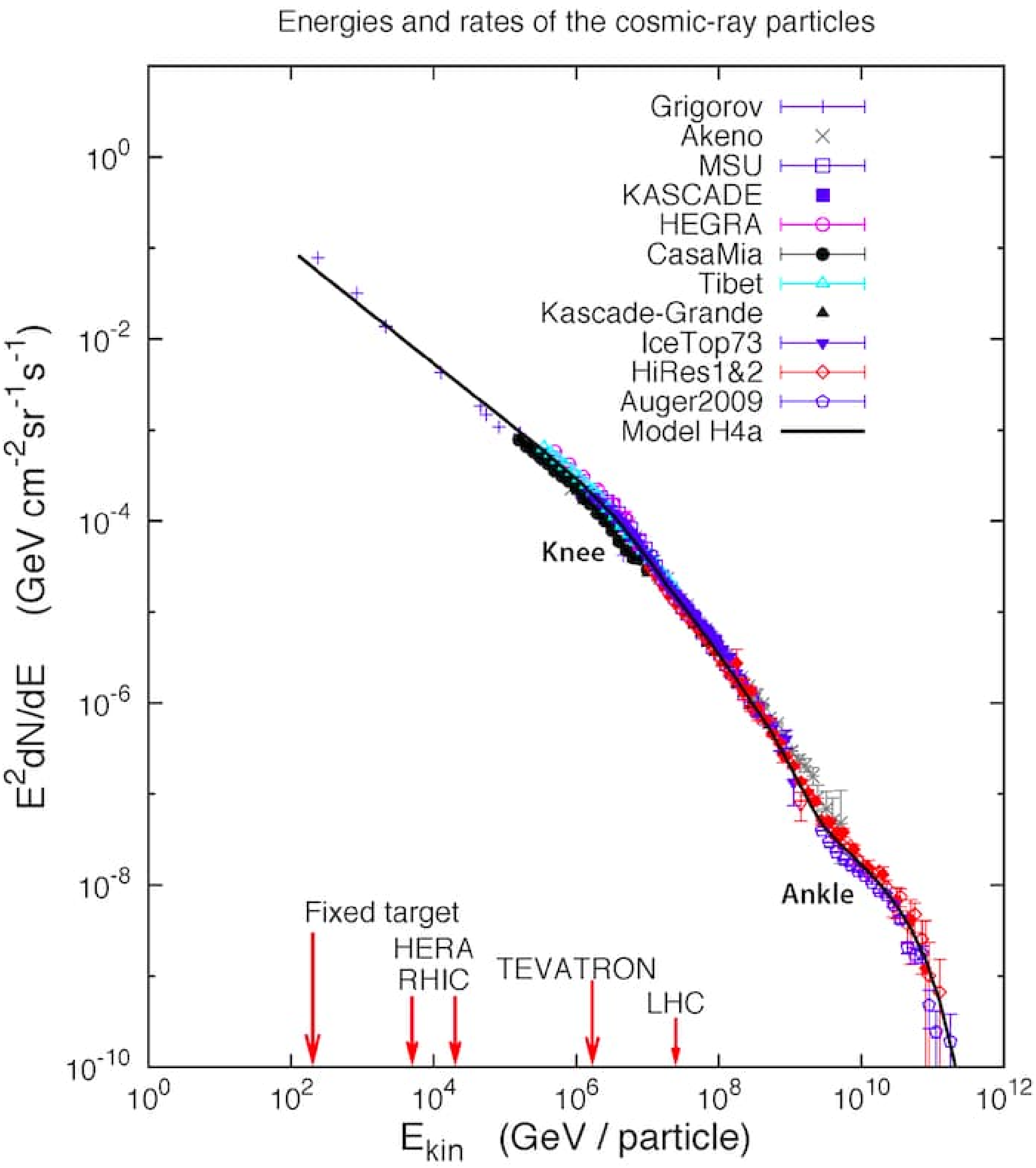


Nobel Prize 1936

The Cosmic Accelerator

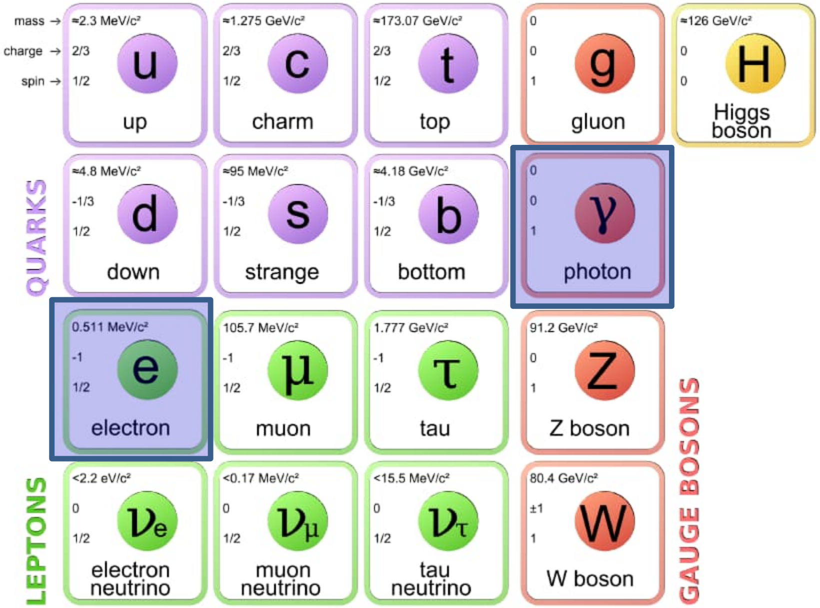


The Cosmic Accelerator flux density of cosmic rays



1912 ~100 years → 2017

- electron
- photons
- nuclei (protons)

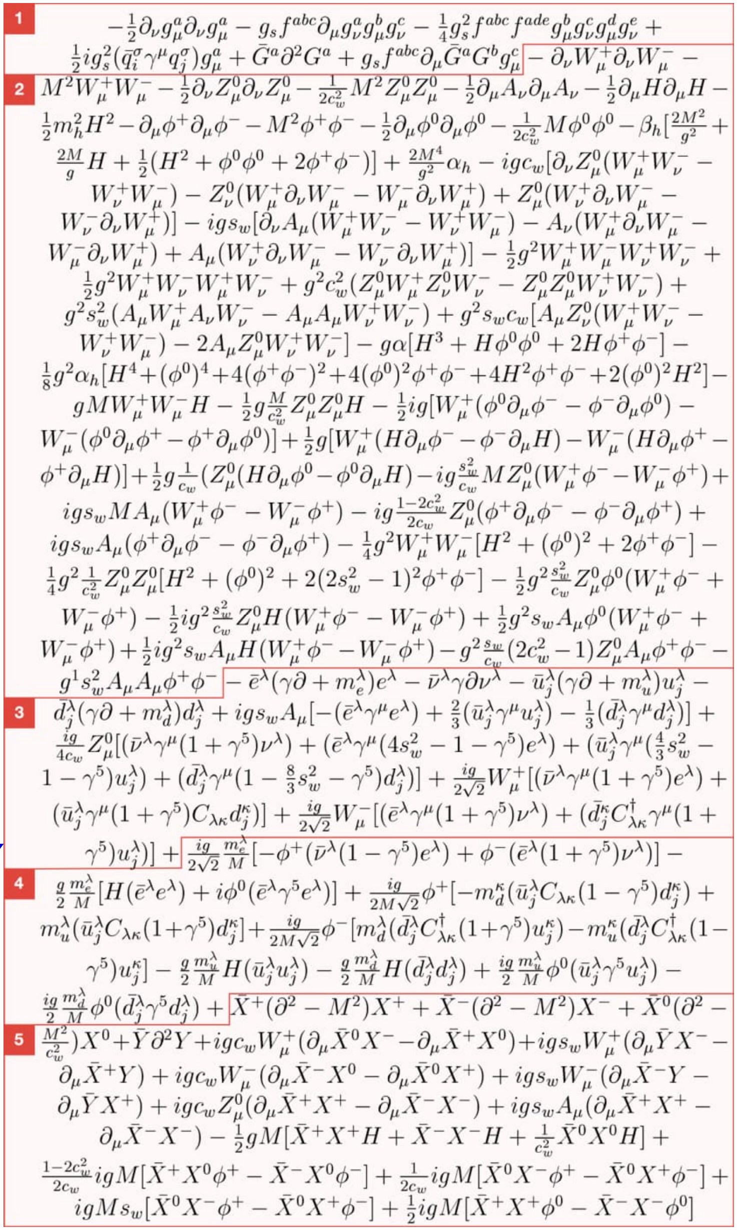


mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	
	0.511 MeV/c^2 -1 1/2 e electron	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	

1912 ~100 years → 2017

- electron
- photons
- nuclei (protons)

Standard Model Lagrangian



1

$$\begin{aligned}&-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\ &\tfrac{1}{2} i g_s^2 (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g^c_\mu\end{aligned}$$

2

$$\begin{aligned}&- \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\ &M^2 W^+_\mu W^-_\mu - \tfrac12 \partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac12 \partial_\mu A_\nu \partial_\mu A_\nu - \tfrac12 \partial_\mu H \partial_\mu H - \\ &\tfrac12 m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \tfrac12\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2} M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \\ &\tfrac{2M}{g}H + \tfrac12(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\ &W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - \\ &W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - \\ &W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \tfrac12 g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\ &\tfrac12 g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\ &g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\ &W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\ &\tfrac18 g^2\alpha_h[H^4+(\phi^0)^4+4(\phi^+\phi^-)^2+4(\phi^0)^2\phi^+\phi^-+4H^2\phi^+\phi^-+2(\phi^0)^2H^2] - \\ &gMW^+_\mu W^-_\mu H - \tfrac12 g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac12 ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\ &W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac12 g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\ &\phi^+\partial_\mu H)] + \tfrac12 g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\ &igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\ &igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac14 g^2 W^+_\mu W^-_\mu[H^2+(\phi^0)^2+2\phi^+\phi^-] - \\ &\tfrac14 g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-] - \tfrac12 g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\ &W^-_\mu\phi^+) - \tfrac12 ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac12 g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\ &W^-_\mu\phi^+) + \tfrac12 ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - \\ &g^1 s_w^2 A_\mu A_\mu\phi^+\phi^-\end{aligned}$$

3

$$\begin{aligned}&- \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar\nu^\lambda\gamma\partial\nu^\lambda - \bar u_j^\lambda(\gamma\partial+m_u^\lambda)u_j^\lambda - \\ &\bar d_j^\lambda(\gamma\partial+m_d^\lambda)d_j^\lambda + igs_wA_\mu[-(\bar e^\lambda\gamma^\mu e^\lambda) + \tfrac23(\bar u_j^\lambda\gamma^\mu u_j^\lambda) - \tfrac13(\bar d_j^\lambda\gamma^\mu d_j^\lambda)] + \\ &\tfrac{ig}{4c_w}Z^0_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar u_j^\lambda\gamma^\mu(\tfrac43 s_w^2 - \\ &1-\gamma^5)u_j^\lambda) + (\bar d_j^\lambda\gamma^\mu(1-\tfrac83 s_w^2-\gamma^5)d_j^\lambda)] + \tfrac{ig}{2\sqrt2}W^+_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + \\ &(\bar u_j^\lambda\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d_j^\kappa)] + \tfrac{ig}{2\sqrt2}W^-_\mu[(\bar e^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d_j^\kappa C^\dagger_{\lambda\kappa}\gamma^\mu(1+ \\ &\gamma^5)u_j^\lambda)] +\end{aligned}$$

4

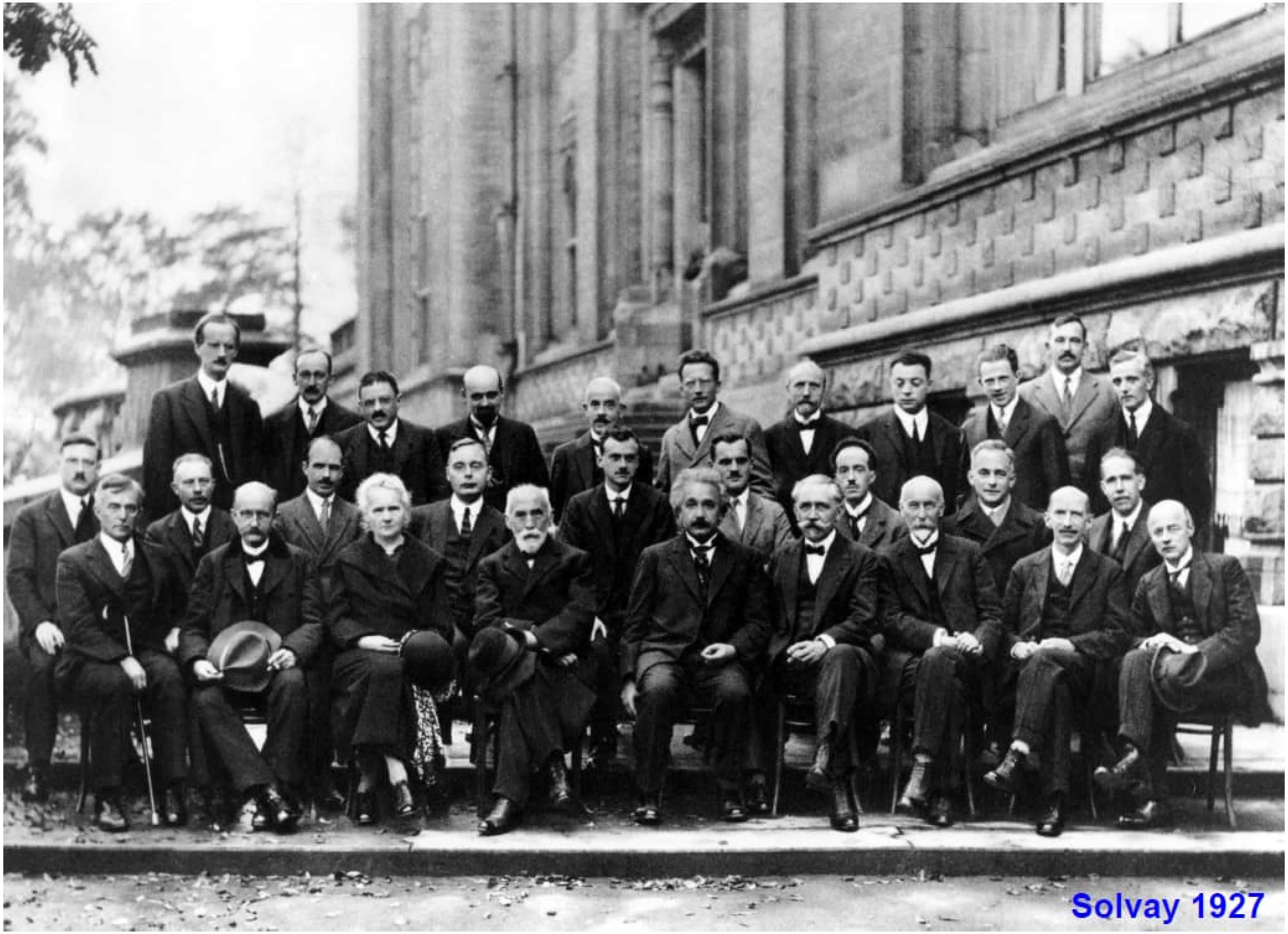
$$\begin{aligned}&\tfrac{ig}{2\sqrt2}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar e^\lambda(1+\gamma^5)\nu^\lambda)] - \\ &\tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar e^\lambda e^\lambda) + i\phi^0(\bar e^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt2}\phi^+[-m_d^\kappa(\bar u_j^\lambda C_{\lambda\kappa}(1-\gamma^5)d_j^\kappa) + \\ &m_u^\lambda(\bar u_j^\lambda C_{\lambda\kappa}(1+\gamma^5)d_j^\kappa] + \tfrac{ig}{2M\sqrt2}\phi^-[m_d^\lambda(\bar d_j^\lambda C^\dagger_{\lambda\kappa}(1+\gamma^5)u_j^\kappa) - m_u^\kappa(\bar d_j^\lambda C^\dagger_{\lambda\kappa}(1- \\ &\gamma^5)u_j^\kappa] - \tfrac g2\tfrac{m_u^\lambda}{M}H(\bar u_j^\lambda u_j^\lambda) - \tfrac g2\tfrac{m_d^\lambda}{M}H(\bar d_j^\lambda d_j^\lambda) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar u_j^\lambda\gamma^5u_j^\lambda) - \\ &\tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar d_j^\lambda\gamma^5 d_j^\lambda) +\end{aligned}$$

5

$$\begin{aligned}&\bar X^+(\partial^2-M^2)X^+ + \bar X^-(\partial^2-M^2)X^- + \bar X^0(\partial^2 - \\ &\tfrac{M^2}{c_w^2})X^0 + \bar Y\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar X^0X^- - \partial_\mu\bar X^+X^0) + igs_wW^+_\mu(\partial_\mu\bar YX^- - \\ &\partial_\mu\bar X^+Y) + igc_wW^-_\mu(\partial_\mu\bar X^-X^0 - \partial_\mu\bar X^0X^+) + igs_wW^-_\mu(\partial_\mu\bar X^-Y - \\ &\partial_\mu\bar YX^+) + igc_wZ^0_\mu(\partial_\mu\bar X^+X^+ - \partial_\mu\bar X^-X^-) + igs_wA_\mu(\partial_\mu\bar X^+X^+ - \\ &\partial_\mu\bar X^-X^-) - \tfrac12 gM[\bar X^+X^+H + \bar X^-X^-H + \tfrac{1}{c_w^2}\bar X^0X^0H] + \\ &\tfrac{1-2c_w^2}{2c_w}igM[\bar X^+X^0\phi^+ - \bar X^-X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-] + \\ &igMs_w[\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-] + \tfrac12 igM[\bar X^+X^+\phi^0 - \bar X^-X^-\phi^0]\end{aligned}$$

1 is ultra specific to the gluon, the boson that carries the strong force
2 is dedicated to explain interactions between bosons, particularly W and Z
3 describes how elementary matter particles interact with the weak force
4 describes how matter particles interact with Higgs ghosts, virtual artifacts
In quantum mechanics, there is no single path a particle can take

Quantum Mechanics



A. Piccard, E. Henriot, P. Ehrenfest, E. Herzen, Th. de Donder, E. Schrödinger, J.E. Verschaffelt, W. Pauli, W. Heisenberg, R.H. Fowler, L. Brillouin
P. Debye, M. Knudsen, W.L. Bragg, H.A. Kramers, P.A.M. Dirac, A.H. Compton, L. de Broglie, M. Born, N. Bohr,
I. Langmuir, M. Planck, M. Curie, H.A. Lorentz, A. Einstein, P. Langevin, Ch.-E. Guye, C.T.R. Wilson, O.W. Richardson

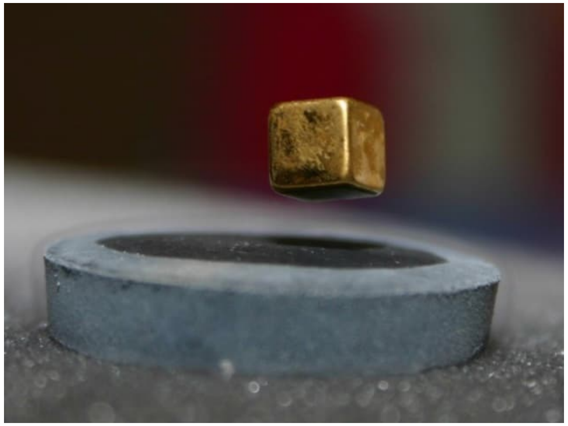
Fermions and Bosons

Fundamental characteristics of particles: ***Spin*** ("self angular momentum")

- Integer values (0, ±1, …) → ***Bosons***
- Half integer values (±1/2, ±3/2, …) → ***Fermions***

Satyendranath Bose

Bosons (Cooper pairs …) can be described by ***common wave function***
→ funny effects (super conductivity, super fluidity, …)



Enrico Fermi

Fermions (electrons or protons …) must be in different states
→ ***Pauli's exclusion principle*** (basis of all chemistry…)

Wolfgang Pauli

Matter Waves for Particles without Spin

	Non relativistic:	Relativistic:
Kinematics:	$E = \frac{\vec{p}^2}{2m}$	$E^2 = p^2c^2 + m^2c^4$
Quantum Mechanics:	$E \rightarrow i\hbar\frac{\partial}{\partial t} \quad and \quad \vec{p} \rightarrow -i\hbar\vec{\nabla}$	$E \rightarrow i\frac{\partial}{\partial t} \quad and \quad \vec{p} \rightarrow -i\vec{\nabla}$
Wave Equation:	$i\hbar\frac{\partial}{\partial t}\psi = \frac{-\hbar^2}{2m}\nabla^2\psi$	$-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\phi = -\nabla^2\phi + \frac{m^2c^2}{\hbar^2}\phi$

density: $\rho(x,t) = |\psi(x,t)|^2$

continuity equation: $\frac{\partial\rho}{\partial t} + \nabla \cdot j = 0$

Schrödinger equation: $\frac{\partial}{\partial t}\psi = \frac{i\hbar}{2m}\nabla^2\psi$

continuity equation: $\frac{\partial}{\partial t}(\psi^*\psi) = -\nabla \cdot \left[\frac{i\hbar}{2m}(\psi\nabla\psi^* - \psi^*\nabla\psi)\right]$

plane waves: $\psi = N \cdot e^{i(p\cdot x - E\cdot t)/\hbar} \qquad E = p^2/2m$

are solutions to the free
Schrödinger equation

p → ***-p*** gives to same result

Matter Waves for Particles without Spin

	Non relativistic:	Relativistic:
Kinematics:	$E = \frac{\vec{p}^2}{2m}$	$E^2 = p^2c^2 + m^2c^4$
Quantum Mechanics:	$E \rightarrow i\hbar\frac{\partial}{\partial t} \quad and \quad \vec{p} \rightarrow -i\hbar\vec{\nabla}$	$E \rightarrow i\frac{\partial}{\partial t} \quad and \quad \vec{p} \rightarrow -i\vec{\nabla}$
Wave Equation:	$i\hbar\frac{\partial}{\partial t}\psi = \frac{-\hbar^2}{2m}\nabla^2\psi$	$-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\phi = -\nabla^2\phi + \frac{m^2c^2}{\hbar^2}\phi$

Klein-Gordon equation

Unlike the Schrödinger equation, the Klein-Gordan equation does not contain factor ***i***. Consequently, it can have both real and complex solutions.

$$\left(\frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \nabla^2 + m^2\right)\phi(x) = 0$$

plane waves:

$$\phi(x) = Ne^{i(p\cdot x - E\cdot t)} = e^{-ip_\mu\cdot x^\mu}$$

satisfies the dispersion relation $E^2 = p^2 + m^2$

continuity equation:

$$\frac{\partial}{\partial t} i\left(\phi^*\frac{\partial\phi}{\partial t} - \phi\frac{\partial\phi^*}{\partial t}\right) = \nabla\cdot[i(\phi^*\nabla\phi - \phi\nabla\phi^*)]$$

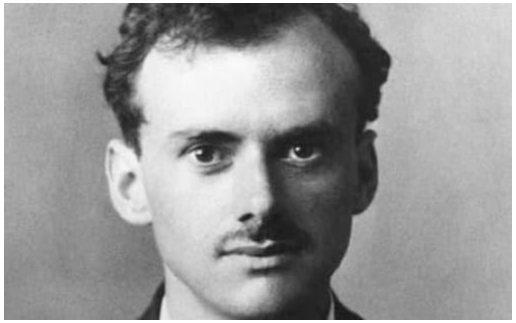
The factor ***i*** is introduced to make the density real

$$\rho = 2|N|^2E \qquad\qquad j = 2|N|^2p$$

Matter Waves for Particles with Spin

$$\left(\beta mc^2 + \sum_{k=1}^{3} \alpha_k p_k c\right)\psi(x,t) = i\hbar \frac{\partial\psi(x,t)}{\partial t}$$

Dirac equation



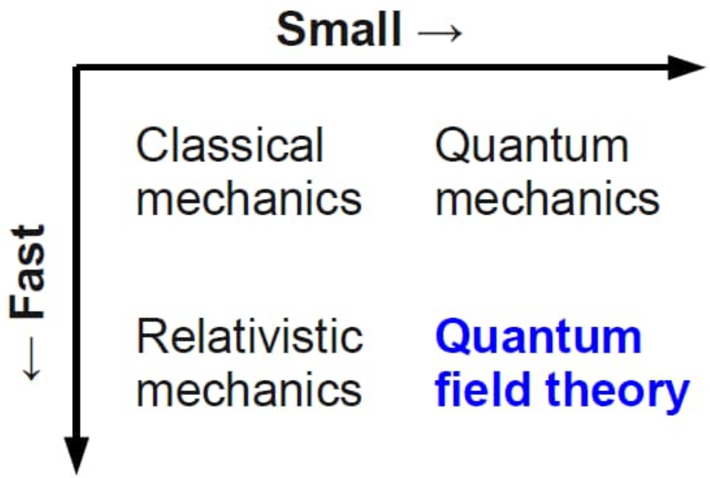
Paul Dirac 1902-1984

The problem with the Klein-Gordon equation: it is second order in derivatives. In 1928, Dirac found the first-order form having the same solutions. α_k and β are 4x4 matrices and Ψ are four-component wave functions: ***spinors*** (for particles with spin ½).

$$i\hbar\gamma^\mu\partial_\mu\psi - mc\psi = 0$$

$$\gamma^0 = \begin{pmatrix} I_2 & 0 \\ 0 & I_2 \end{pmatrix} \qquad \gamma^1 = \begin{pmatrix} 0 & \sigma_x \\ -\sigma_x & 0 \end{pmatrix} \qquad \gamma^2 = \begin{pmatrix} 0 & \sigma_y \\ -\sigma_y & 0 \end{pmatrix} \qquad \gamma^3 = \begin{pmatrix} 0 & \sigma_z \\ -\sigma_z & 0 \end{pmatrix}$$

Quantum Field Theory



Small →

← Fast

Classical mechanics

Quantum mechanics

Relativistic mechanics

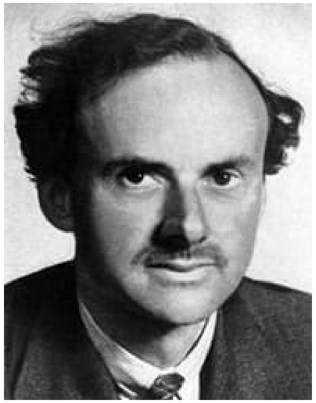
Quantum field theory

- **First major achievement:** Dirac’s equation for free electrons (and positrons)

$$E^2 = (mc^2)^2 + (pc)^2$$

$$\boxed{E = \pm\sqrt{p^2c^2 + m^2c^4}}$$

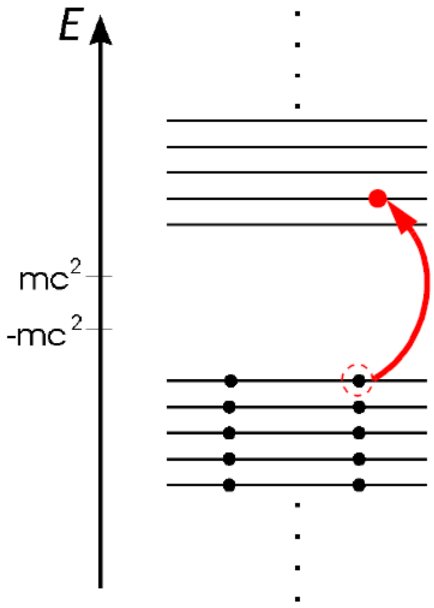
- **Interpretation of negative energies:** sea of electrons → holes in sea act as positively charged electrons → confirmed by Anderson 1932



Paul Dirac
1902-1984
Nobel Prize 1933

Carl Anderson
1905-1991
Nobel Prize 1936

Dirac's Picture of Vacuum



Fermions in Dirac's representation

The "hole" created by the appearance of the electron with a positive energy is interpreted as the presence of electron's ***antiparticle*** with the opposite charge.

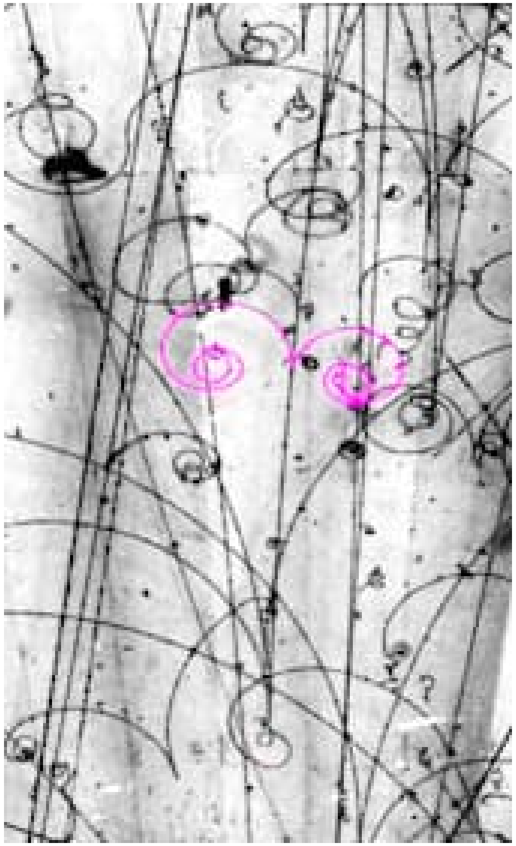
"negative" energy → antiparticles

Later, Feynman – Stückelberg interpretation: antiparticles are particles travelling in revers time direction

- Every charged particle has the antiparticle of the same mass and opposite charge.

Antimatter

- Antiparticles look and behave just like their corresponding matter particles, except they have opposite charges.



evidence for antimatter in this early **bubble chamber photo**.

The **magnetic field** in this chamber makes negative particles curl left and positive particles curl right.

The antielectron is called ***positron*** and is designated e^+.

Discovery of the Positron

- First observed by D. Skobeltsyn in cosmic rays, using a Wilson cloud chamber (1929)
- C. D. Anderson: study of cosmic rays in a cloud chamber (1932)

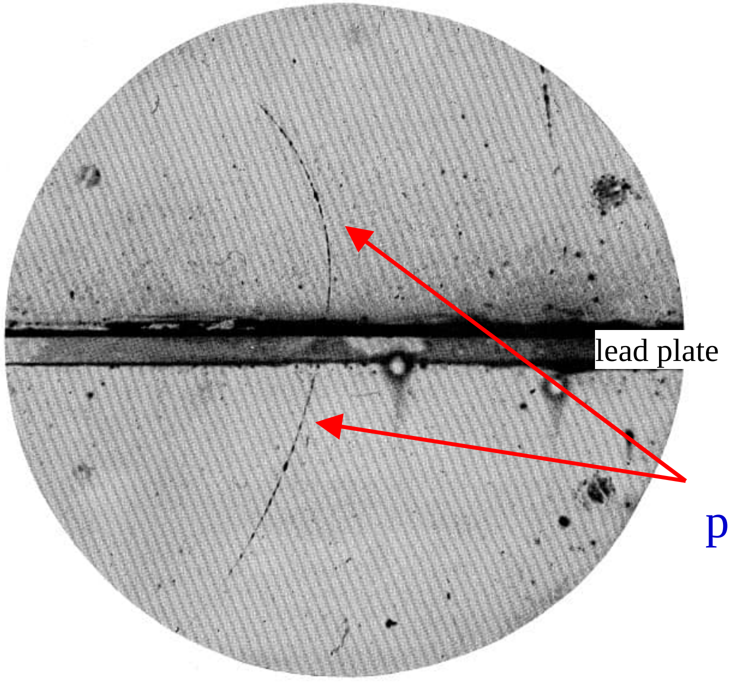


FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

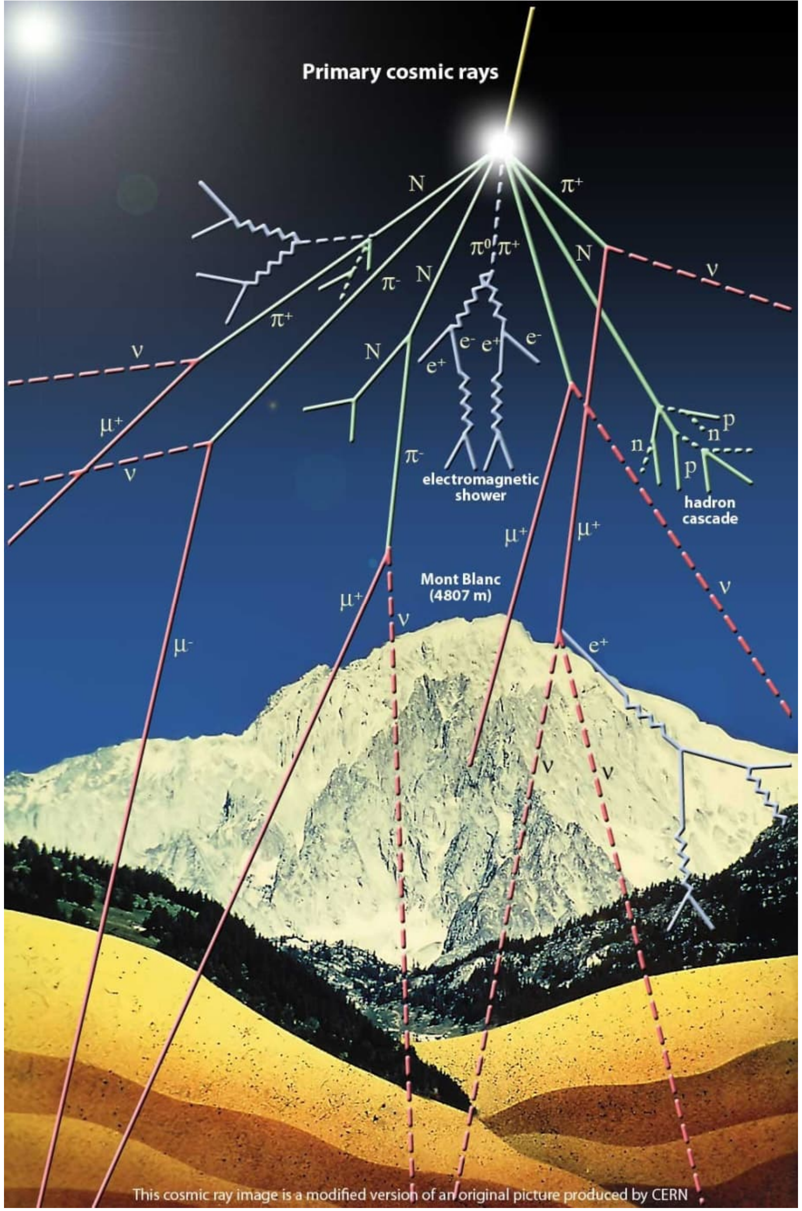
positron track

positrons are bent due to
Lorentz force in magnetic field

proof of existence of antiparticles

Carl D. Anderson; Nobel Prize 1936

Muon Discovery (1936)



This cosmic ray image is a modified version of an original picture produced by CERN

Carl D. Anderson; Nobel Prize 1936

Muon-Lepton discovery in cosmic rays by

Carl D. Anderson
\+
Seth Nedermeyer

mass: $m_\mu \sim 100$ MeV

- The muon is the first “exotic” particle
- It was believed to be the meson predicted by Yukawa

Prediction of the Pion

Hideki Yukawa
1907-1981

H. Yukawa predicted 1935 mesons as carriers of the strong force

$$meson\ mass \sim \hbar c\,/(range\ of\ force)$$

$$range \sim 1\ fm \quad \rightarrow \quad m_{meson} = 200\ MeV$$

$\hbar c = 197.326\ MeV\ fm$

note 1: ***mesons are quark-antiquark $q\bar{q}$*** states and <u>not elementary</u>

note 2: meson = “mean, intermediate state”

The range of forces is related to the mass of exchange particle M. An amount of energy $\Delta E = Mc^2$ borrowed for a time Δt is governed by the Uncertainty Principle:

$$\Delta E \cdot \Delta t \sim \hbar$$

The maximum distance the particle can travel is $\Delta x = c \cdot \Delta t$, where c is the velocity of light.

$$\Delta x = \hbar c / \Delta E$$

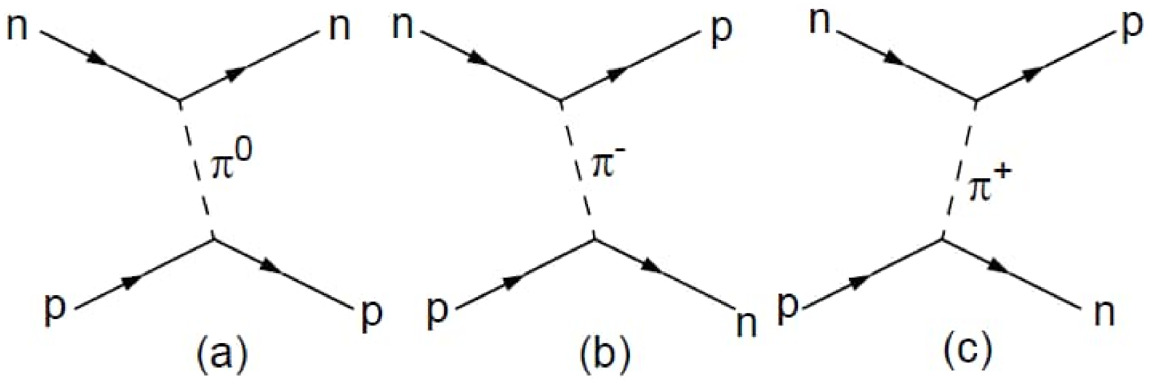
$$\boxed{\Delta x = \hbar c / M c^2}$$

- The photon has M = 0 → infinite range of EM force.
- W boson has a mass of 80 GeV/c^2 → range of weak force $\Delta x = 2 \cdot 10^{-3}\ fm$

Nobel Prize 1949

Discovery of Pions

Discovered pions were fitting very well into Yukawa’s theory – they were supposed to be responsible for the nuclear force:

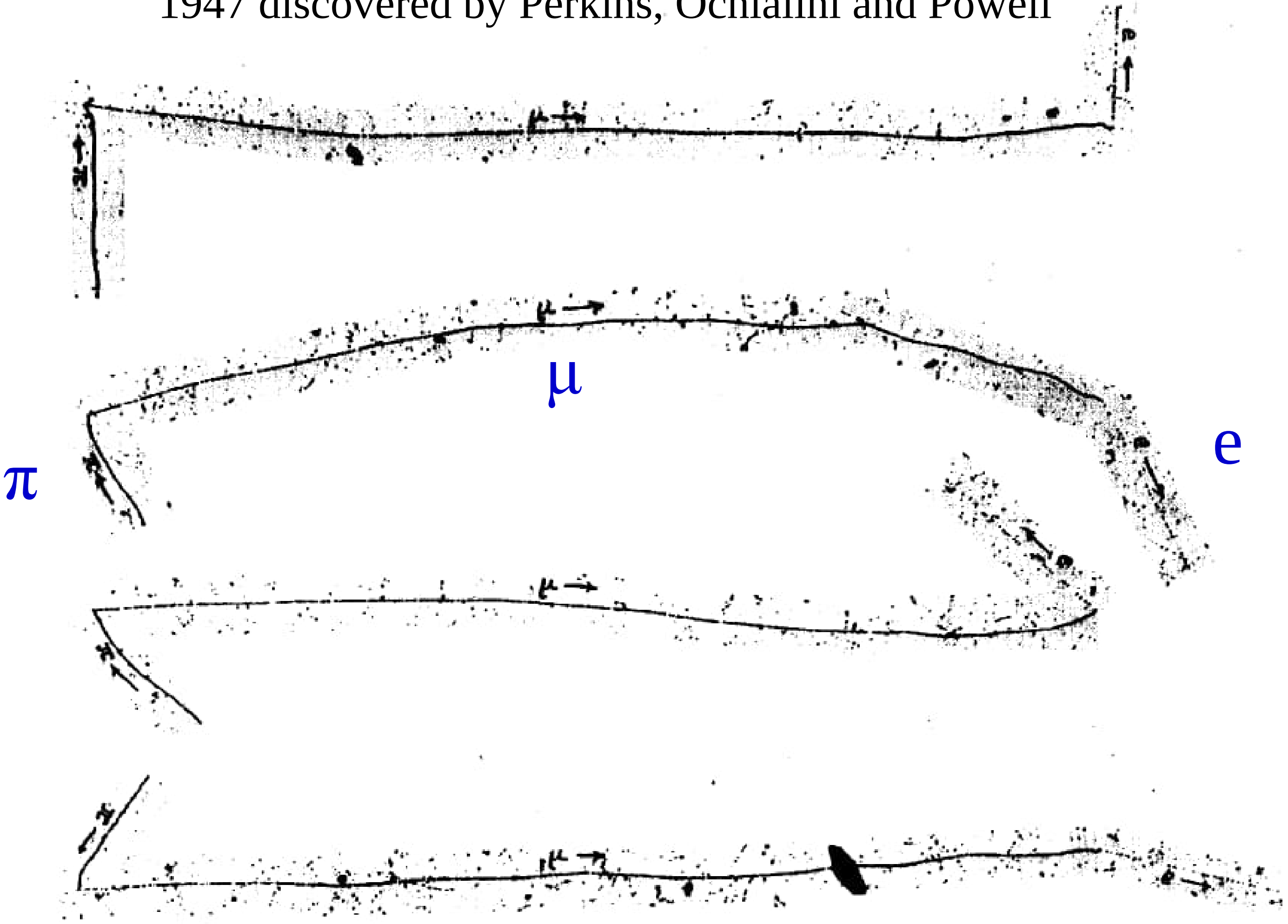


Yukawa model of direct (a) and exchange (b, c) nuclear force

- The resulting potential for this kind of exchange is of Yukawa type and at the longest range reproduces observed nuclear forces very well, including even spin effects.
- However, at the ranges comparable with the size of nucleons, this description **fails**, and the internal structure of hadrons must be taken into account.

Discovery of the Pion

1947 discovered by Perkins, Ochialini and Powell



First observed pions: a π^+ stops in the emulsion and decays to a μ^+ and ν_μ, followed by the decay of μ^+.

Powell; Nobel Prize 1950

Discovery of the Pion

Some reactions induced by cosmic rays primaries:

$$\begin{aligned} p + p &\rightarrow p + n + \pi^+ \\ &\rightarrow p + p + \pi^0 \\ &\rightarrow p + p + \pi^+ + \pi^- \end{aligned}$$

Same reactions can be reproduced in accelerators, with higher rates, although cosmic rays may provide higher energies.

Discovery of the Pion

In emulsions, pions were identified by much more dense ionization along the track, as compared to electrons.

The figure shows examples of the reaction

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

where pion comes to the rest, producing muons having equal energies, which in turn decay by the reaction $\mu^+ \rightarrow e^+ \nu_e \overline{\nu_\mu}$

- Charged pions decay mainly to the muon-neutrino pair (branching ratio about 99.99%), having lifetimes of $2.6 \cdot 10^{-8}$ s. In quark terms:

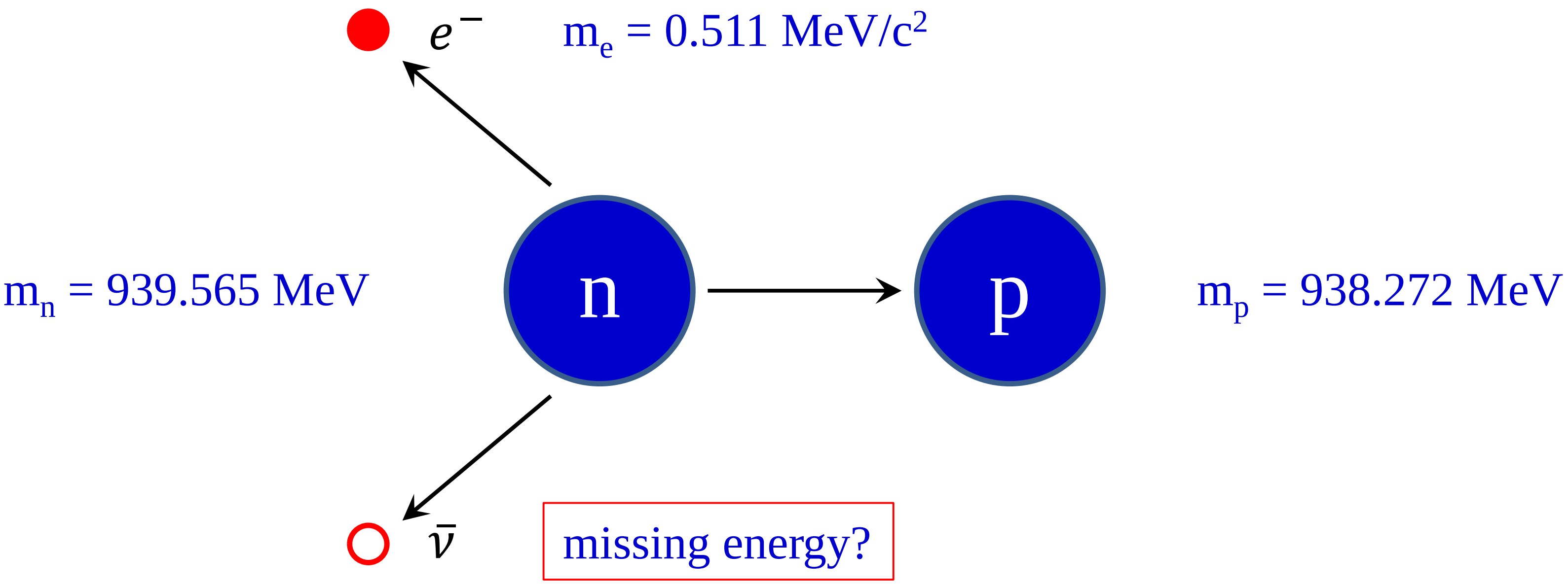
$$(u\bar{d}) \rightarrow \mu^+ + \nu_\mu$$

- Neutral pions decay mostly by the electromagnetic interaction, having shorter lifetimes of $0.8 \cdot 10^{-16}$ s:

$$\pi^0 \rightarrow \gamma + \gamma$$

Beta Decay

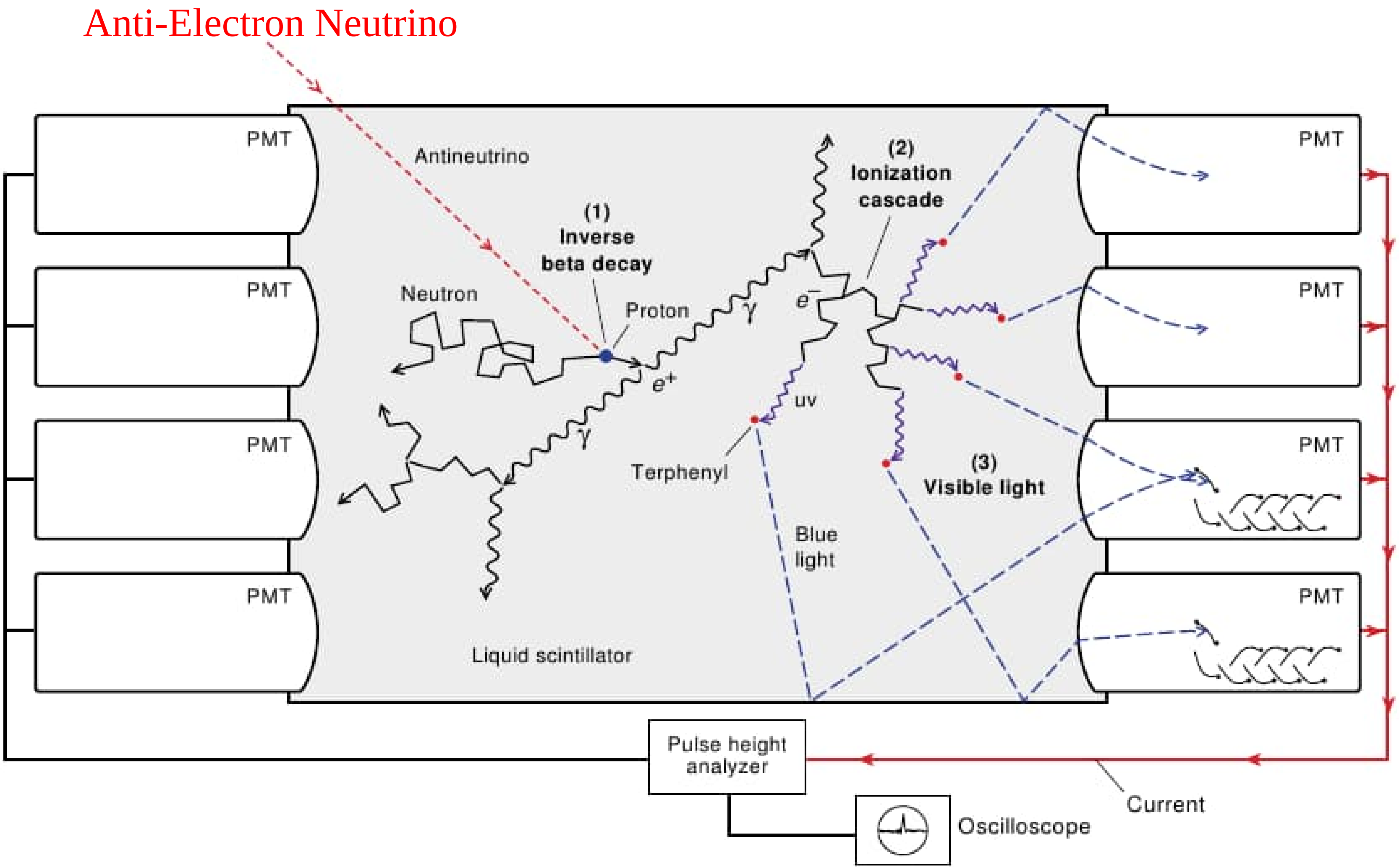
$beta\ decay: \quad n \rightarrow p + e^{-} + \bar{\nu}$



W. Pauli predicted in a letter to E. Fermi the existence of neutrinos (1930)

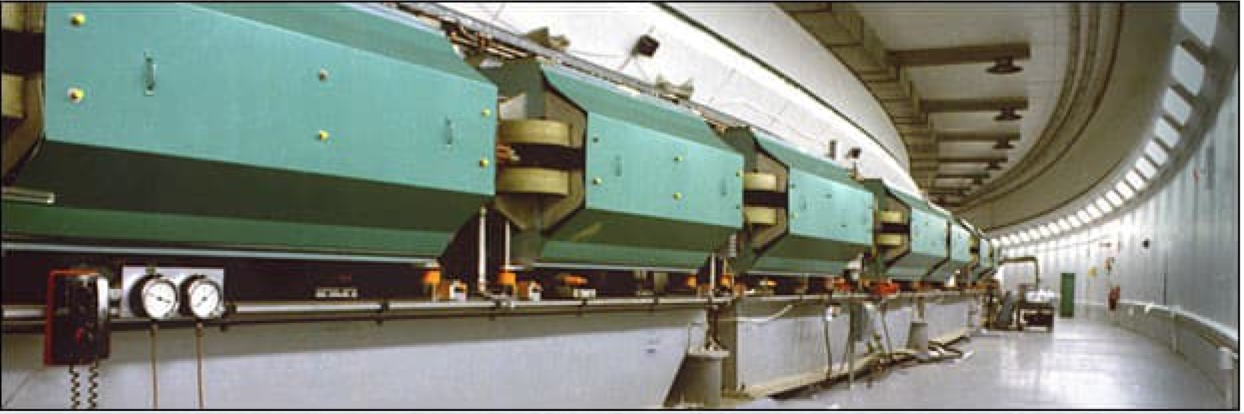
Discovery of the Electron-Neutrino

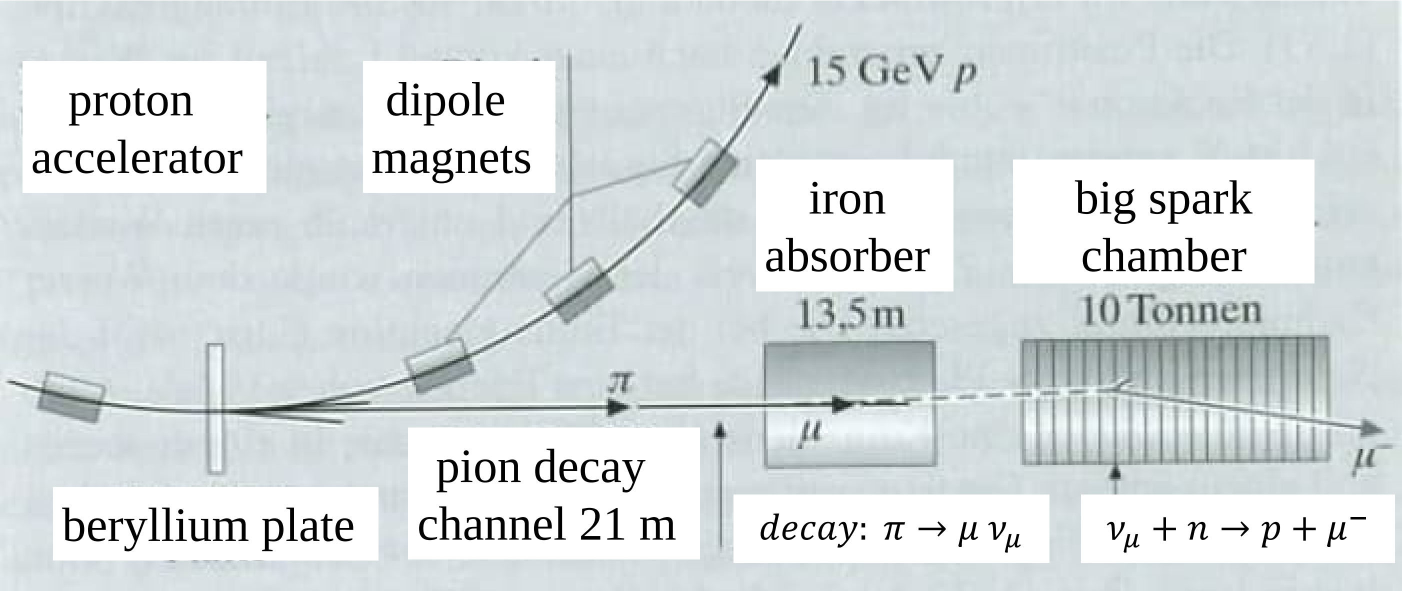
Discovery of the ***electron neutrino*** (Cowan, **Reines**, 1957)



Nobel Prize 1995

Existence of Muon-Neutrinos





proton accelerator

dipole magnets

iron absorber

big spark chamber

beryllium plate

pion decay channel 21 m

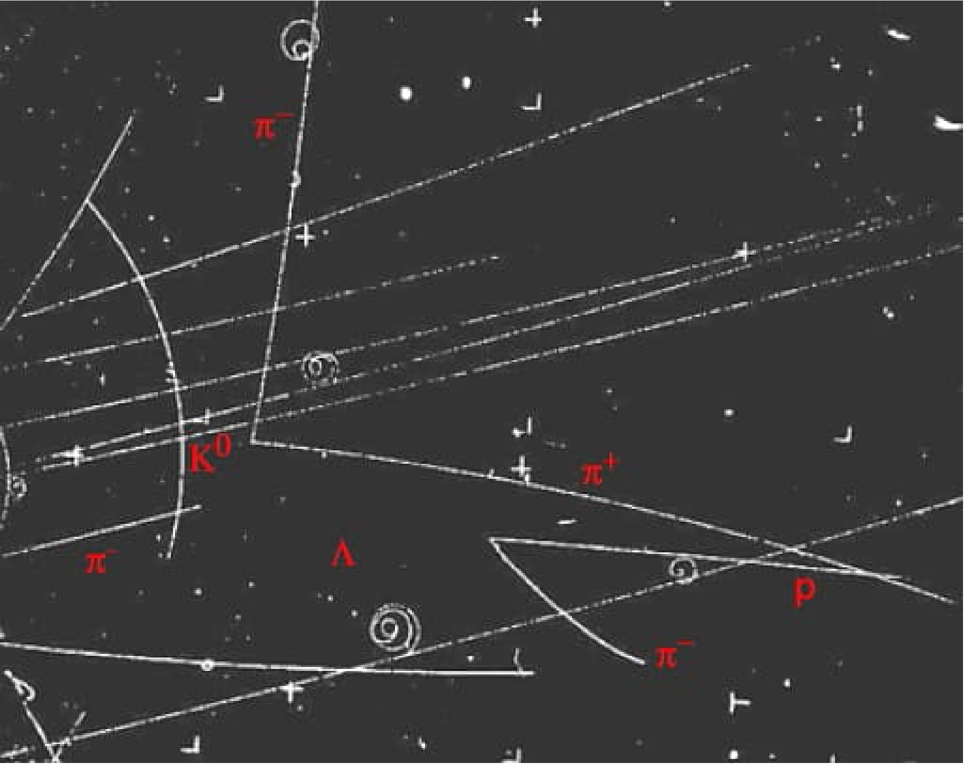
decay: $\pi \rightarrow \mu\, \nu_\mu$

$\nu_\mu + n \rightarrow p + \mu^-$

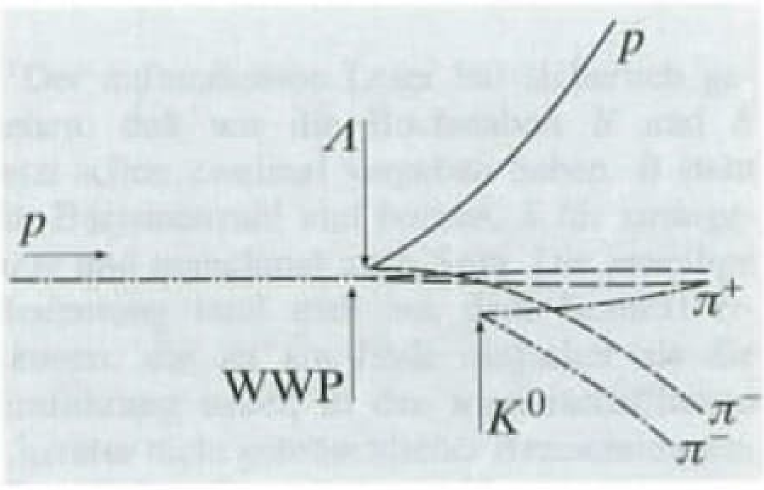
Discovery of the ***muon neutrino*** (Ledermann, Schwartz, Steinberger 1962)

Nobel Prize 1988

Discovery of Strangeness Surprise!



A bubble chamber picture of the above reaction



"V-particles"

Production of ***Kaons*** and
$K^+(u\bar{s})$, $K^0\left(d\bar{s}/s\bar{d}\right)$, $K^-(s\bar{u})$

Lambda-Baryons (uds) in pp-collisions

Long lifetime!!!
neither electromagnetic nor strong force

(1950ties)

How does a bubble chamber work:

- It is filled with a liquid under pressure (hydrogen)
- Particles ionize the liquid along their passage
- When pressure drops, liquid boils preferentially along the ionization trails

Discovery of Strangeness

Strange mesons and baryons

were called so because, being produced in strong interactions, had quite long lifetimes and decayed weakly rather than strongly.

The most light particles containing s-quark are:

- mesons K^+. K^- and K^0, $\overline{K^0}$: “Kaons”, lifetime of K+ is $1.2 \cdot 10^{-8}$ s
- baryon Λ, lifetime of $2.6 \cdot 10^{-10}$ s

Principle decay modes of strange hadrons:

$$K^+ \rightarrow \mu^+ + \nu_\mu \qquad (B=0.64)$$

$$K^+ \rightarrow \pi^+ + \pi^0 \qquad (B=0.21)$$

$$\Lambda \rightarrow \pi^- + p \qquad (B=0.64)$$

$$\Lambda \rightarrow \pi^0 + n \qquad (B=0.36)$$

While the first decay in the list is clearly a weak one, decays of Λ can be very well described as strong ones, if not the long lifetime: $(udd) \rightarrow (d\bar{u}) + (uud)$ must have a lifetime of order 10-23 s, thus Λ can not be another sort of neutron…

B ≡ branching

Discovery of Strangeness

Solution: to invent a new ***"strange"*** quark, bearing a new quark number – ***"strangeness",*** which does not have to be conserved in weak interactions

S = 1	**S = -1**
	Λ (1116) = uds
K^+ (494) = $u\bar{s}$	K^- (494) = $s\bar{u}$
K^0 (498) = $d\bar{s}$	$\overline{K^0}$ (498) = $s\bar{d}$

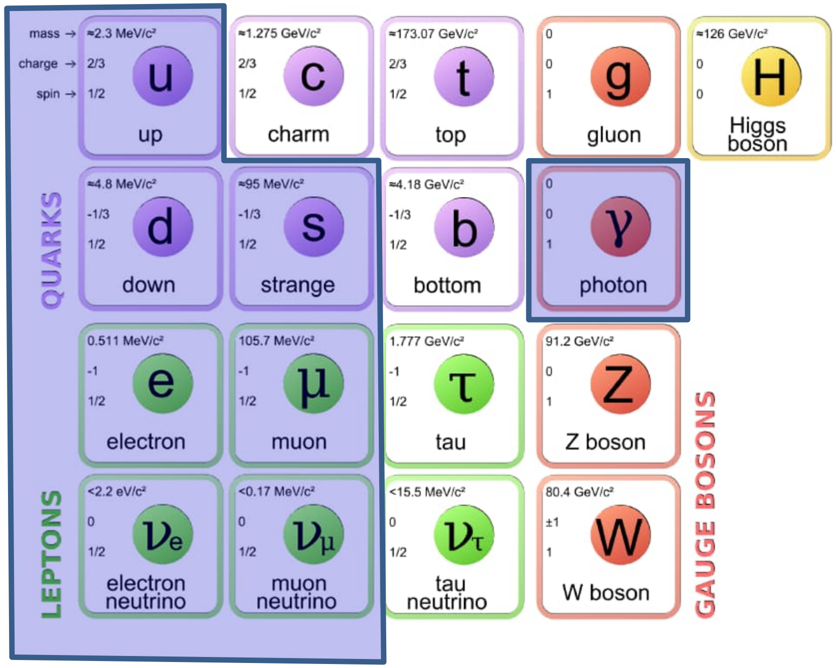
- In strong interactions, strange particles have to be produced in pairs in order to conserve total strangeness ***("associated production")***:

$$\pi^- + p \rightarrow K^0 + \Lambda$$

In 1952, ***bubble chambers*** were invented as particle detectors, and also worked as ***targets***, providing, for instance, the proton target for the above reaction.

Status in 1962 – (50 years after Hess ’balloon trip)

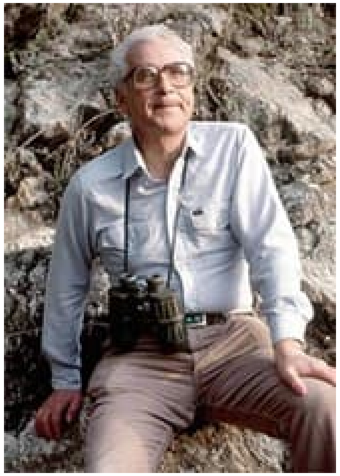
known fermions



M. Gell-Mann and G. Zweig
hypnotized existence of quarks:

- up-quark
- down-quark
- strange-quark

in the year 1964



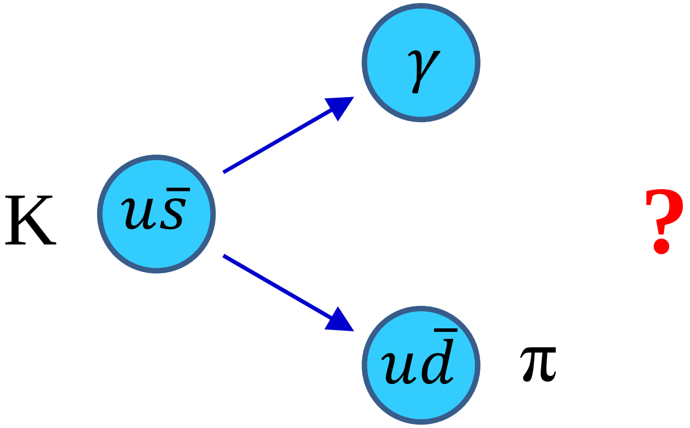
Murray Gell-Mann
1929-

George Zweig
1937-

Nobel Prize 1969

Prediction of the Charm-Quark

How explain non-observation of Flavor Changing Neutral Currents? $\boxed{K \nrightarrow \pi\,\gamma}$



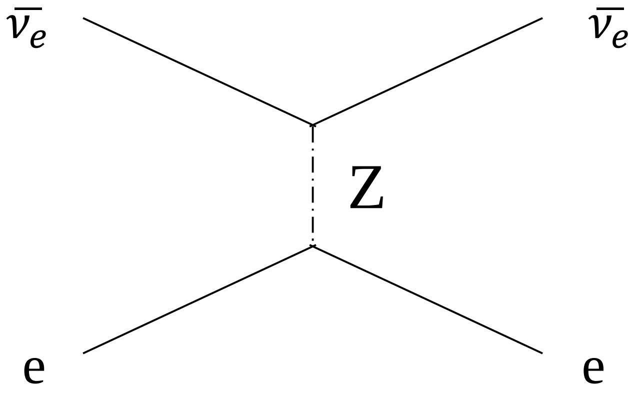
Such a **flavor changing** decay is forbidden if a **fourth quark** exists
(Glashow, Iliopoulos, Maiani)

prediction

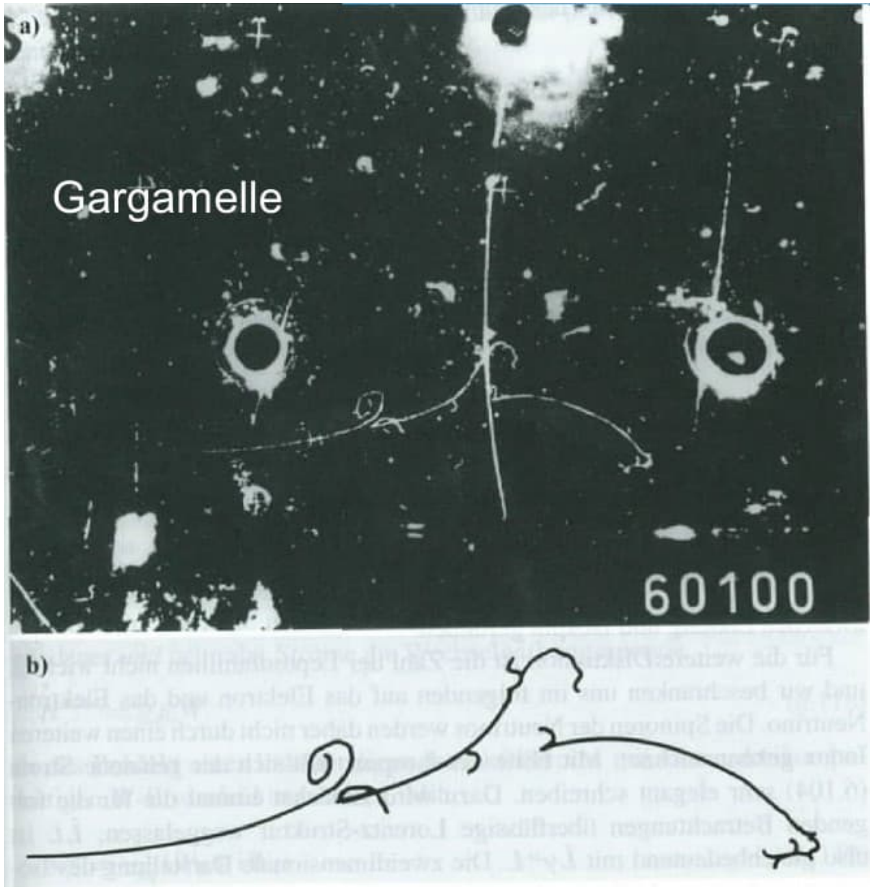
Note: Kaon and Pion have similar quantum numbers!

Observation of Neutral Currents

$\bar{\nu}_e \, e \rightarrow \bar{\nu}_e \, e$



Bubble Chamber Gargamelle (1974)



We find interactions without visible incoming or outgoing particle.

Observation of the Charm-Quark

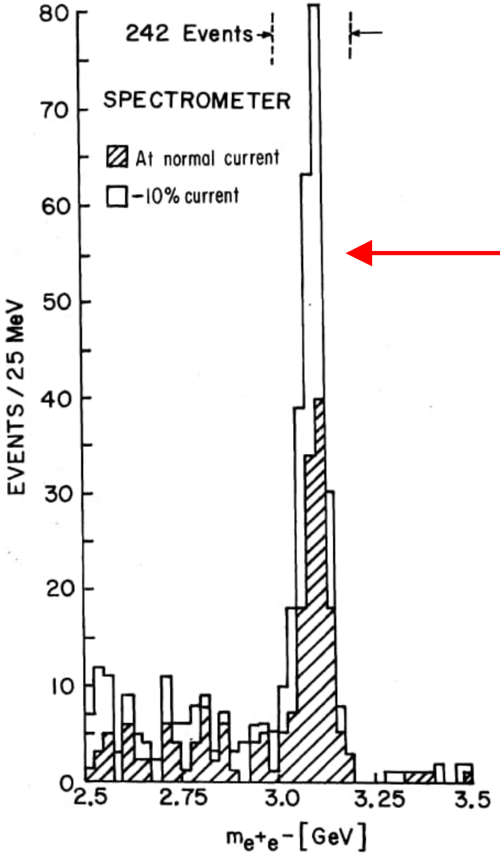


FIG. 2. Mass spectrum showing the existence of *J*. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

$c\bar{c}$

resonance

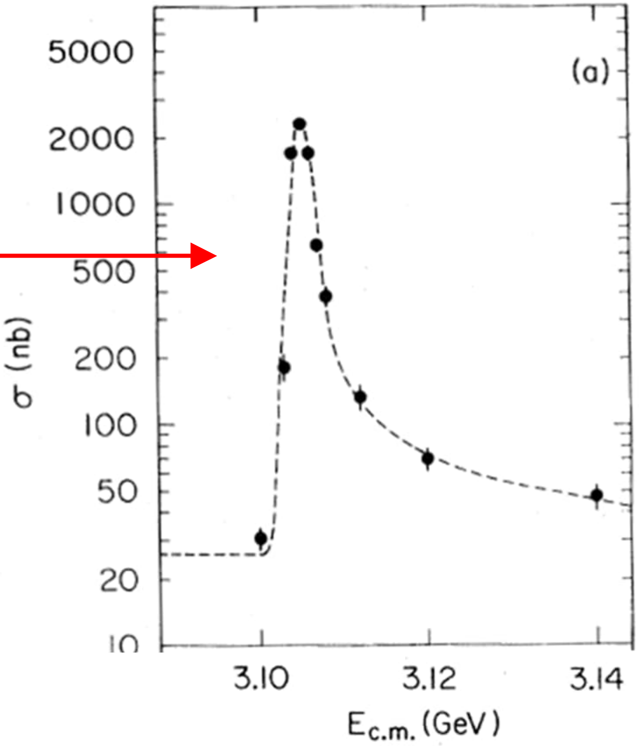


FIG. 1. Cross section versus energy for (a) multi-hadron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^- final states. The curve in (a) is the expected shape of a δ-function resonance folded with the Gaussian energy spread of the beams and including radiative processes. The cross sections shown in (b) and (c) are integrated over the detector acceptance. The total hadron cross section, (a), has been corrected for detection efficiency.

p Be → X J/Psi → X e^+e^-

BNL: **S. Ting** et al. (1974)

e^+e^- → J/Psi → e^+e^- ($\mu^+\mu^-$), ($\pi^+\pi^-$)

SLAC: B. Richter et al. (1974)

Nobel Prize 1976

Discovery of Charm-Quark

- Bubble chambers were great tools of particle discovery, providing physicists with numerous hadrons, all of them fitting *u*-*d*-*s* quark scheme until 1974.

- In 1974, a new particle was discovered, which demanded a new flavour to be introduced. Since it was detected simultaneously by two rival groups in Brookhaven (BNL) and Stanford (SLAC), it received a double name:

$$J/\Psi\,(3097) = c\bar{c}$$

The new quark was called ***"charmed"***, and the corresponding quark number is ***charm***, C. Since J/Ψ itself has C = 0, it is said to contain "hidden charm".

Shortly after that particles with "naked charm" were discovered as well:

$$D^{+}(1869) = c\bar{d}, \qquad D^{0}(1865) = c\bar{u}$$

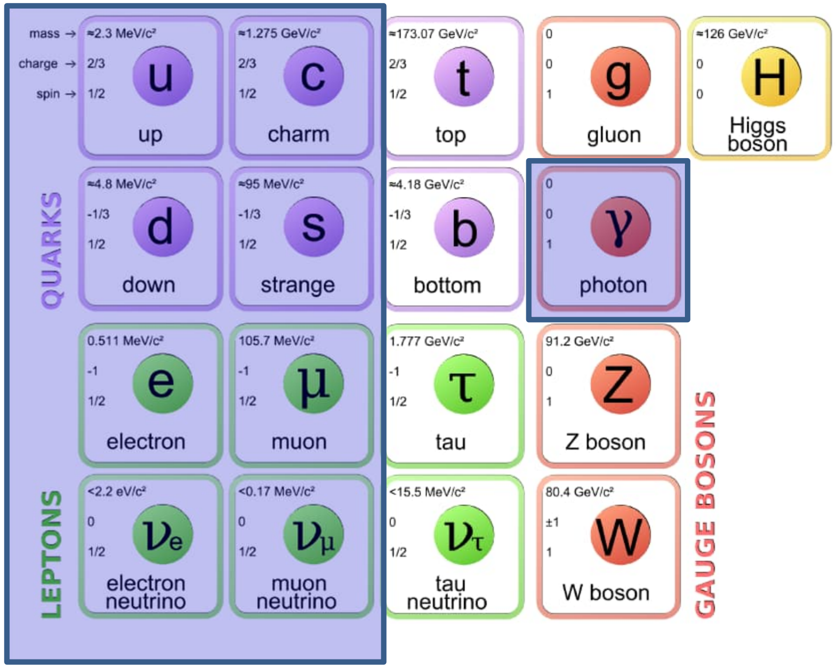
$$D^{-}(1869) = d\bar{c}, \qquad D^{0}(1865) = cu$$

$$\Lambda_c^{+}(2285) = udc$$

Status in 1975

known fermions

no anti-matter in universe!



Charge and Parity Conservation must be broken!
(2nd A. Sakharovs condition)

→ **third quark family** could explain matter – anti-matter asymmetry
Nambu, Kobayashi, Maskawa

Note: particle physics and evolution of universe are closely related!

Nobel Prize 2008

Discovery of Charm- and Bottom-Quark

Even heavier charmed mesons were found – those which contained strange quark as well:

$$D_S^+(1969) = c\bar{s} \qquad D_S^-(1969) = s\bar{c}$$

Lifetimes of the lightest charmed particles are of order 10-13 s, well in the expected range of weak decays.

❖ Discovery of "charmed" particles was a triumph for the electroweak theory, which demanded number of quarks and leptons to be equal.

In 1977, ***"beautiful"*** mesons were discovered:

$$Y(9460) = b\bar{b}$$

$$B^+(5279) = u\bar{b} \qquad B^0(5279) = d\bar{b}$$

$$B^-(5279) = b\bar{u} \qquad B^0(5279) = b\bar{d}$$

and the lightest b-baryon: $\Lambda_b^0(5461) = udb$

And this is the limit: top-quark is too unstable to form observable hadrons

Discovery of the Third Family

Tau Lepton discovered by MARK1 at SPEAR (1974-1976)

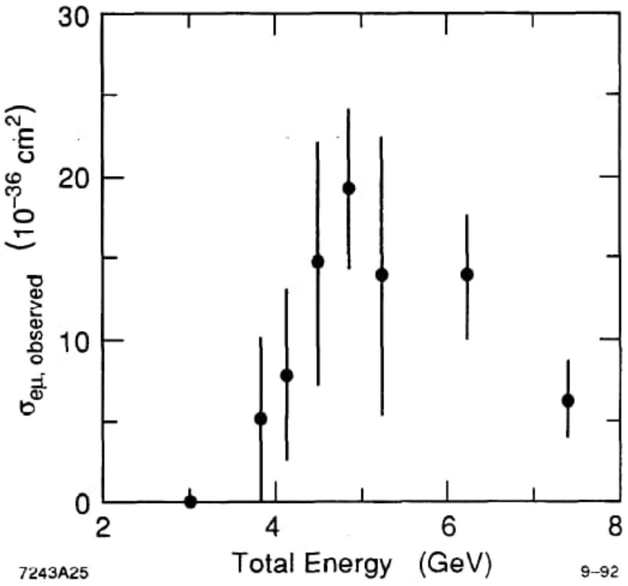


Fig. 4. From Perl *et al.* (1975): the observed cross section for the signature $e\mu$ events from the Mark I experiment at SPEAR. This observed cross section is not corrected for acceptance. There are 86 events with a calculated background of 22 events.

$$e^+e^- \rightarrow \tau^+\tau^-$$

$$\tau \rightarrow e\,\nu\nu$$

$$\tau \rightarrow \mu\,\nu\nu$$

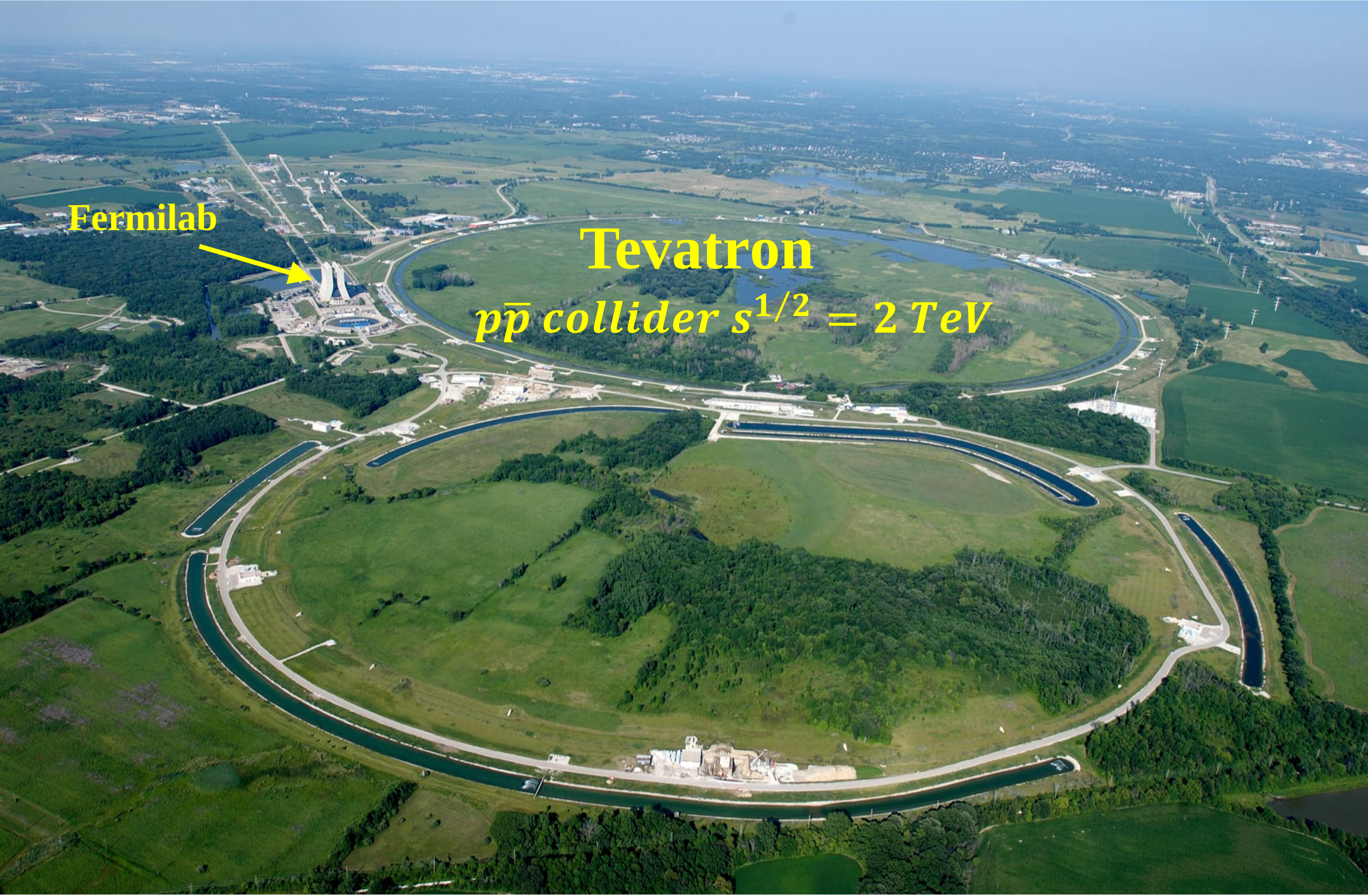
$$\boxed{m_\tau = 1.777\ GeV}$$

discovery of ***tau-lepton***

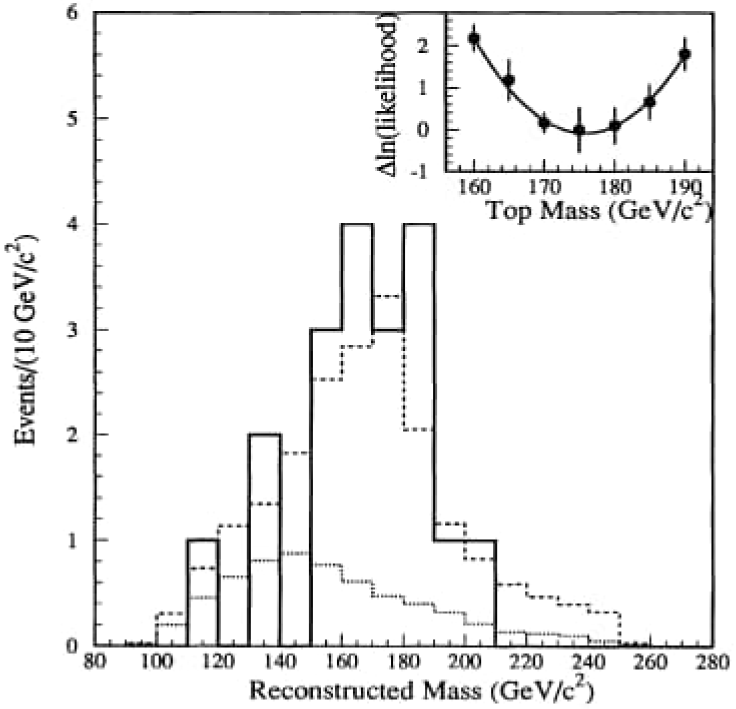
(Reines et al., M. Perl Nobel Prize 1995**)**

Discovery of the ***Bottom-Quark*** (1977) by **M. Ledermann et al.** Nobel Prize 1988

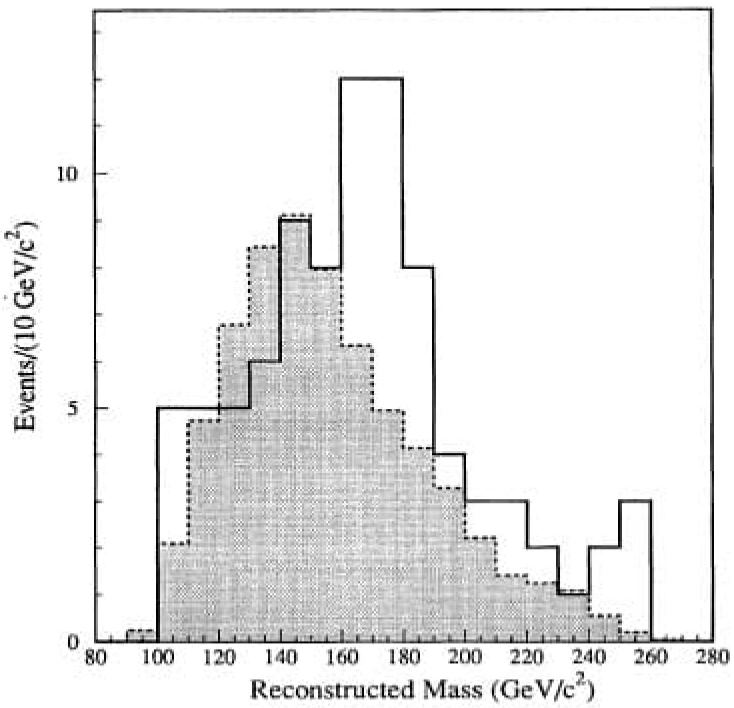
Top-Quark Discovery at Tevatron



Top-Quark Discovery in 1995



CDF Collaboration



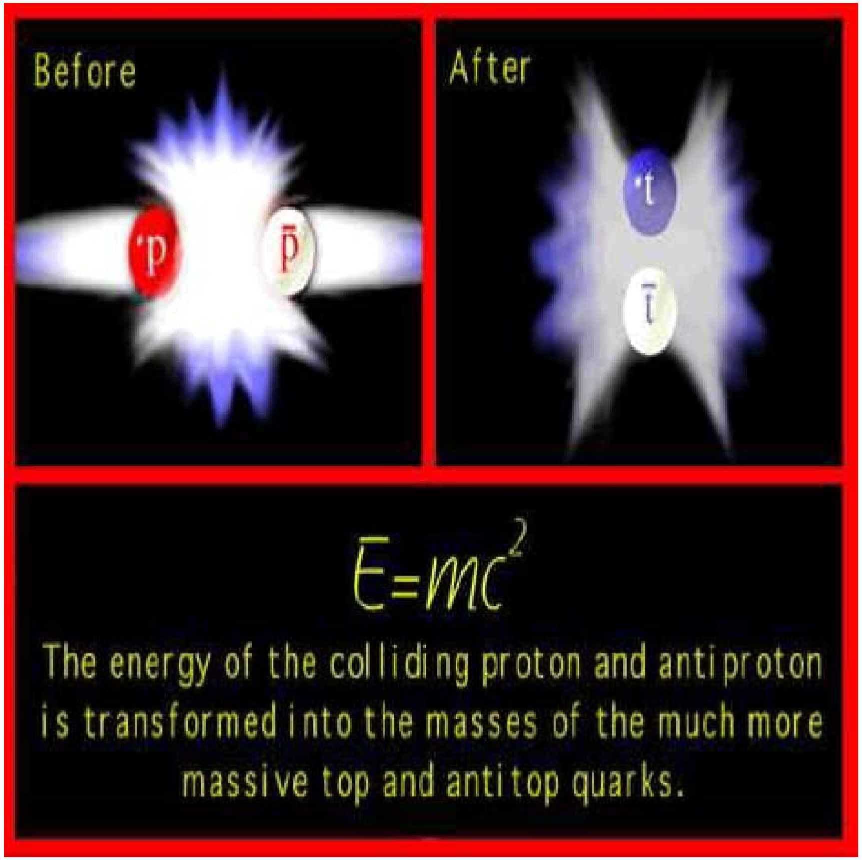
C0 Collaboration

Top-Quark mass ~ 175 GeV

Top production: $p\bar{p} \to t\bar{t}\;X$

Top decay: $t \to W\;b \quad and \quad W \to q\bar{q}$

Top-Quark Discovery in 1995



$$E=mc^2$$

The energy of the colliding proton and antiproton is transformed into the masses of the much more massive top and antitop quarks.

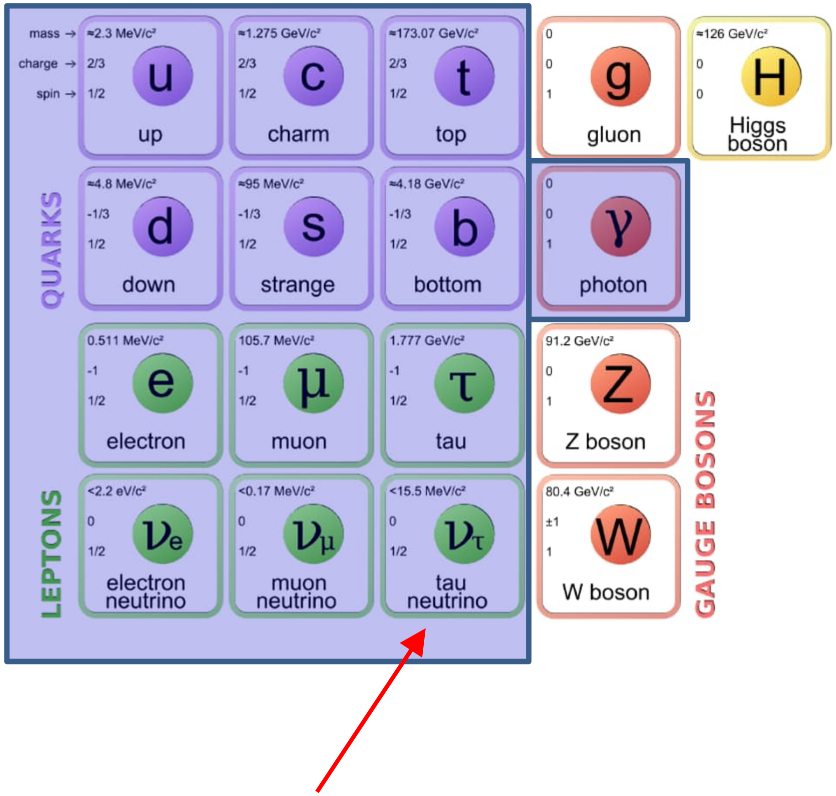
Top-Quark mass ~ 175 GeV

Top production: $p\bar{p} \rightarrow t\bar{t}\,X$

Top decay: $t \rightarrow W\ b \quad and \quad W \rightarrow q\bar{q}$

Status in 2000 (~90 years after Hess balloon trip)

all fermions discovered

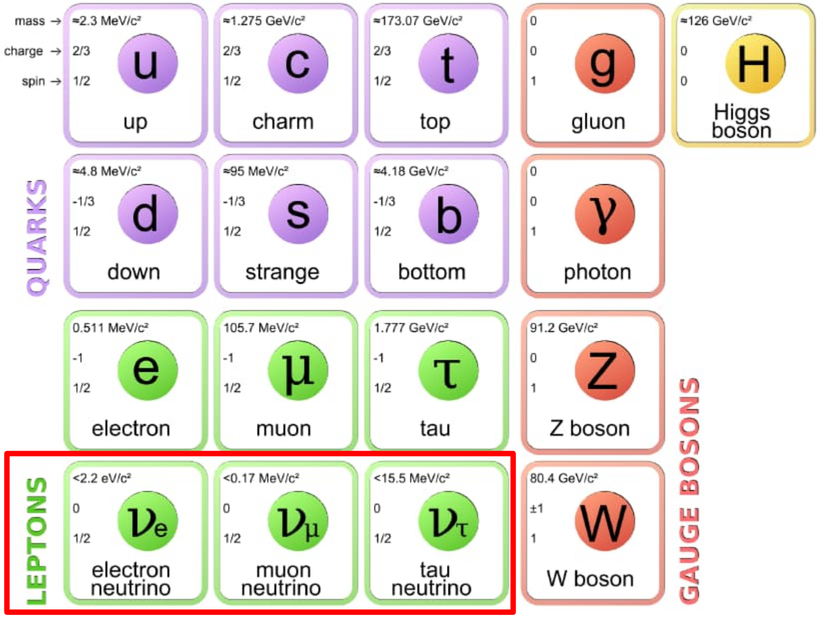


tau-neutrino discovered
in 2000 by Donut experiment

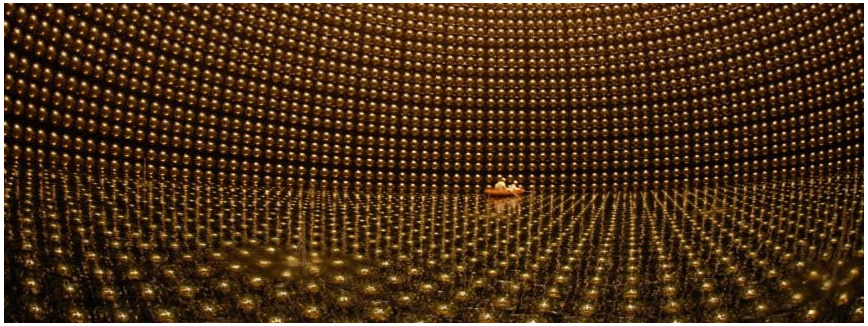
Status in 2002 (~90 years after Hess balloon trip)

Nobel Prize 2015

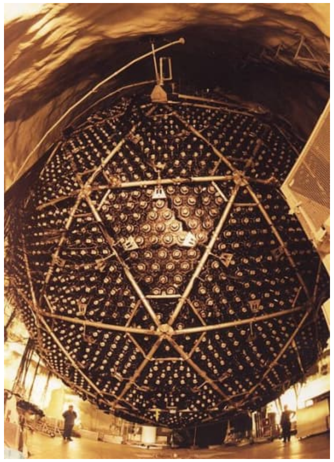
Takaaki Kajita + Arthur B. McDonald



neutrinos have mass!



Super-Kamiokande (1998)



SNO experiment (2001/2)

Discovery of Vector-Bosons

Photons:

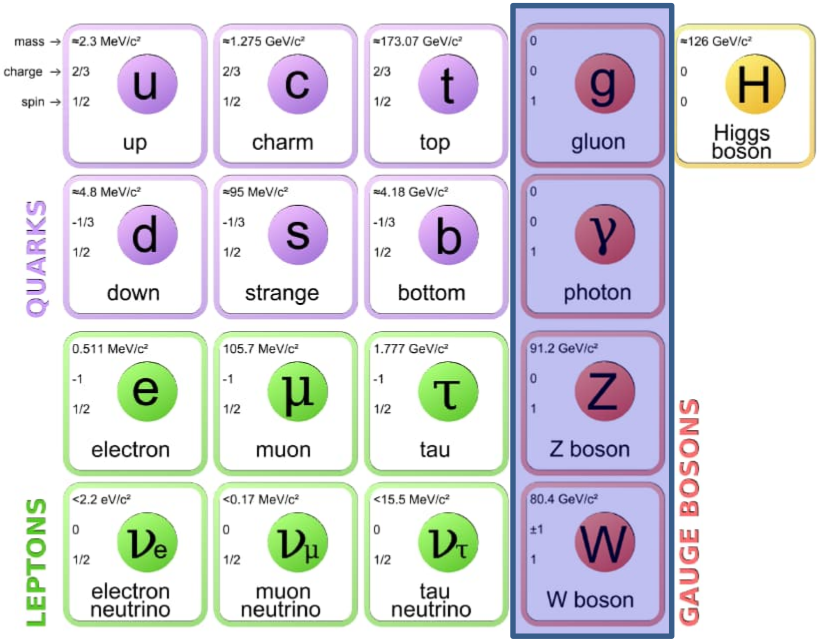
- X-rays (Röntgen 1895) → Nobel Prize 1901
- photo-electric effect (Einstein 1905) → Nobel Prize 1921

Gluons:

- 8 carriers of strong force
- predicted by Gell-Mann et al.
- experimental discovery as jets of hadrons (e.g. PETRA)

$W^{\pm}$ bosons:

- carriers of weak interactions
- responsible for weak decays
- building blocks of "**Standard Model**"
  Glashow, Salam, Weinberg → Nobel Prize 1979
- W-boson discovered at CERN $Sp\bar{p}S$ in 1983
  C. Rubbia and S. van der Meer → Nobel Prize 1984

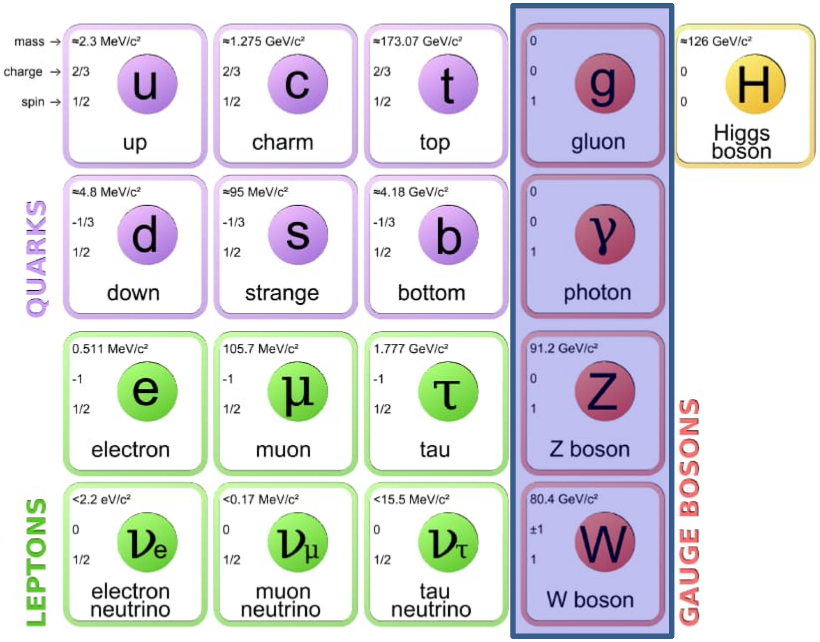


Abdus Salam, Steven Weinberg, Sheldon L. Glashow

Discovery of Vector Bosons

***Z-boson*:**

- indirectly observed at Gargamelle
- discovered at CERN $Sp\bar{p}S$ in 1983
  C. Rubbia and S. van der Meer → Noble Prize 1984
- precision studies at LEP accelerator



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	

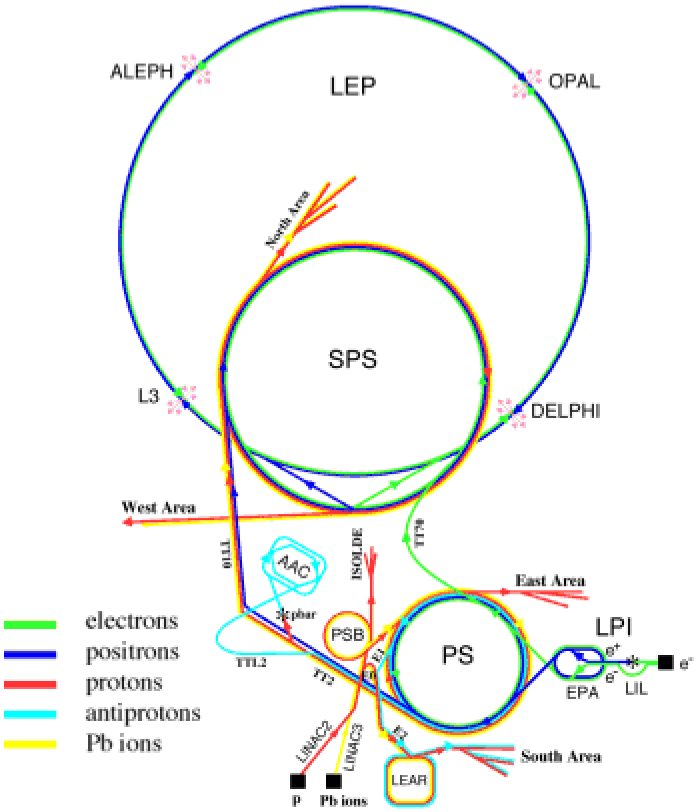
Large Electron Positron (LEP) collider

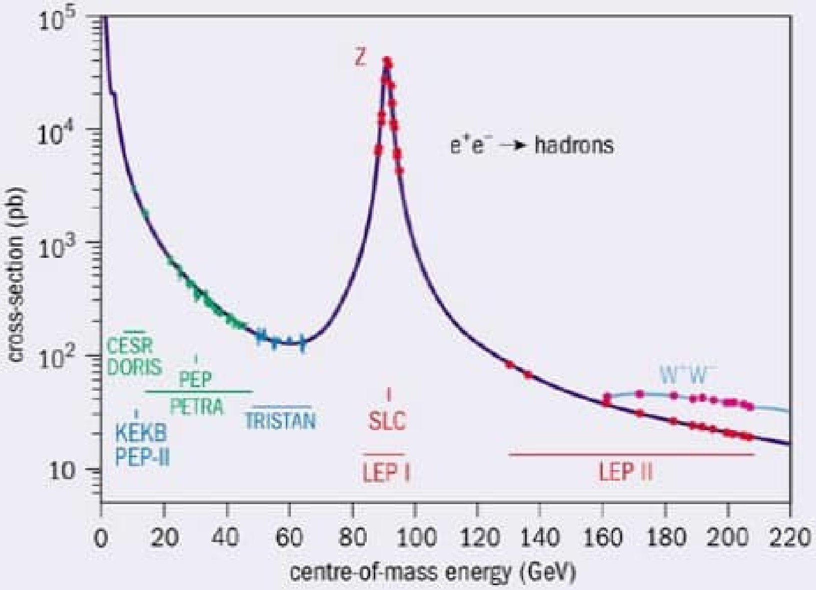
Carlos Rubbia

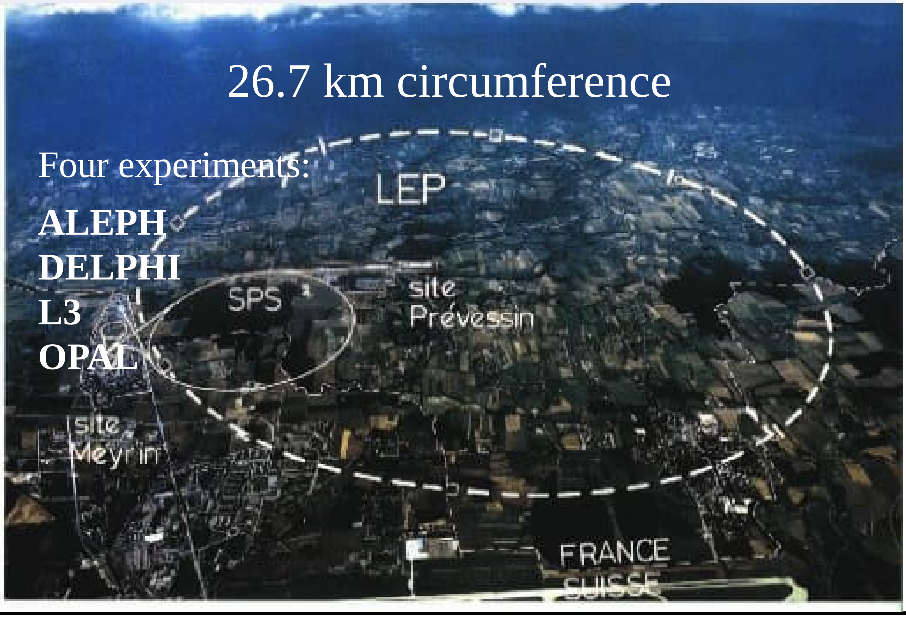
Simon van der Meer

Large Electron-Positron Collider at CERN

1989-2000: $S^{1/2}$ = 90-200 GeV





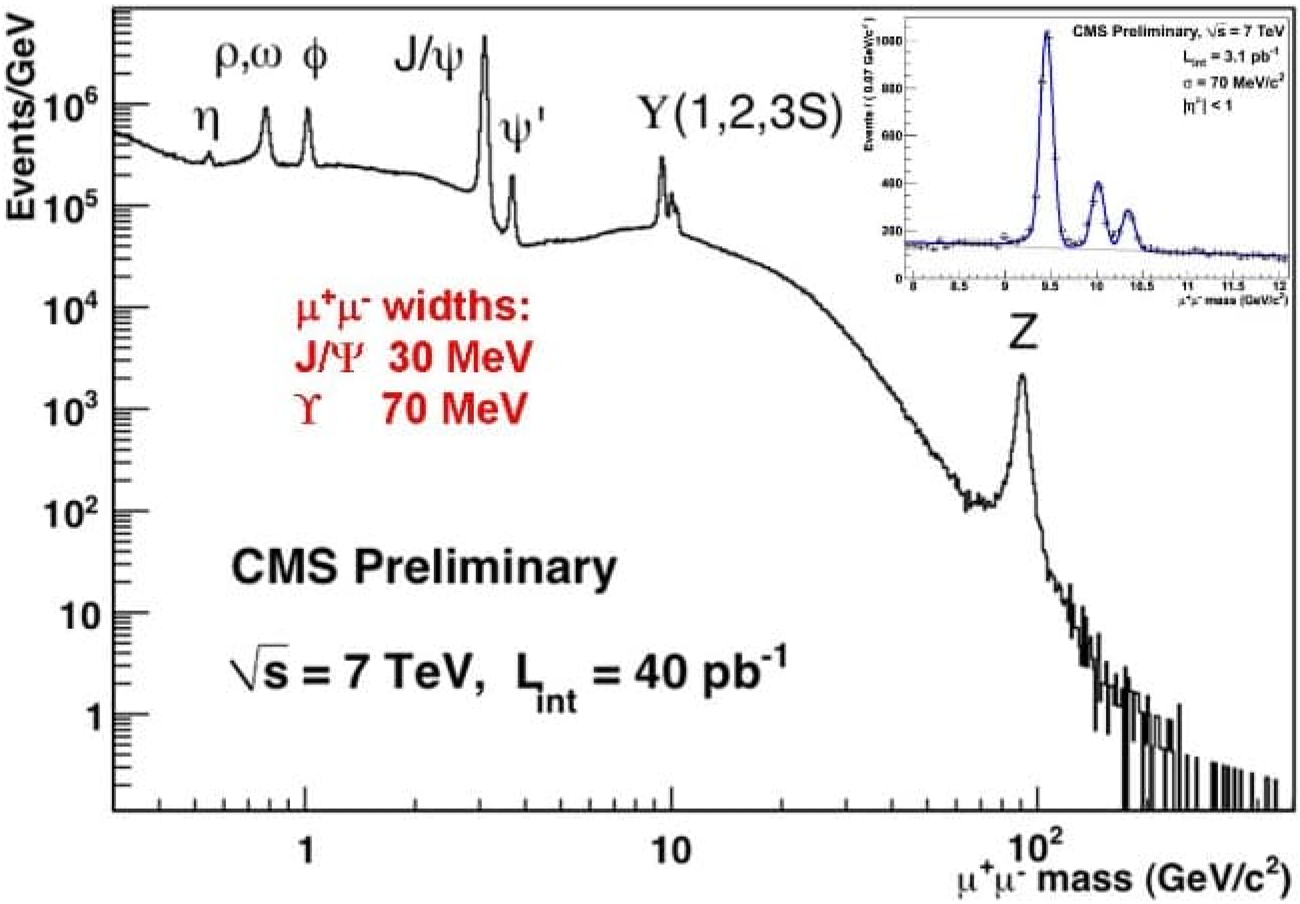


26.7 km circumference

Four experiments:

ALEPH
DELPHI
L3
OPAL

Large Electron-Positron Collider at CERN



Large Hadron Collider at CERN

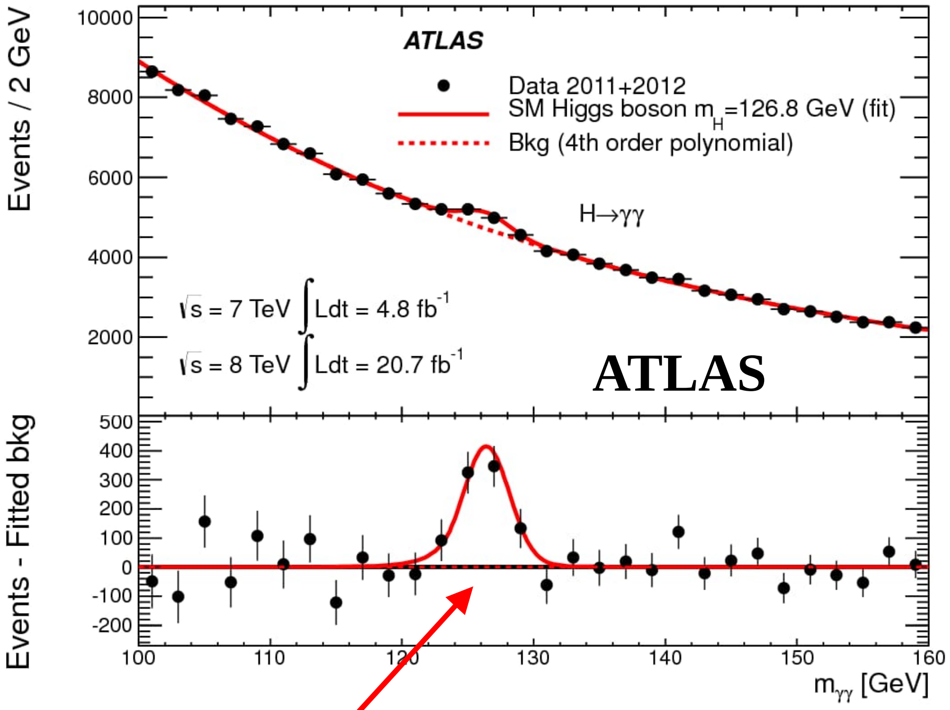
LHC $(p \rightarrow \leftarrow p)$

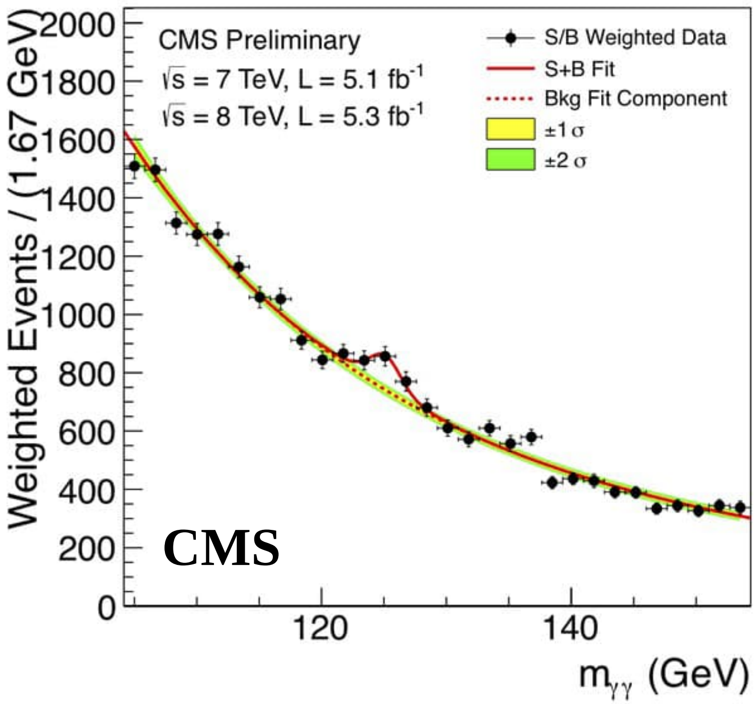
$s^{1/2} \leq 14$ TeV

26.7 km circumference

- 40000 tons of cold mass spread over 27 km
- 10000 tons of Liquid Nitrogen (at T = 80 K)
- 60 tons of Liquid Helium (cools ring to final 1.9 K)

The Higgs-Boson





M_H = 125 GeV

Nobel Prize 2013
F. Englert
P. Higgs

CMS - Collaboration