PHL424: Nuclear and Particle Physics

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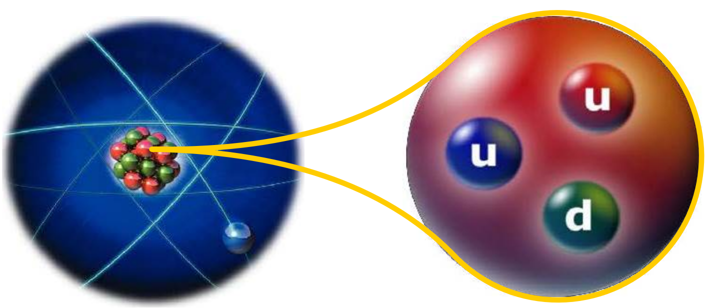
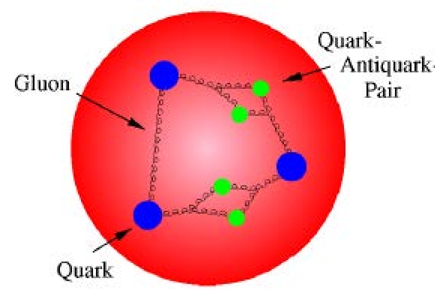
Wednesday	9:55 – 10:45
Thursday	10:50 – 11:40
Friday	11:45 – 12:35
Friday(T)	8:00 – 8:50

Tutor: Kanhaiya Jha (kanhaiya.jha@iitrpr.ac.in)

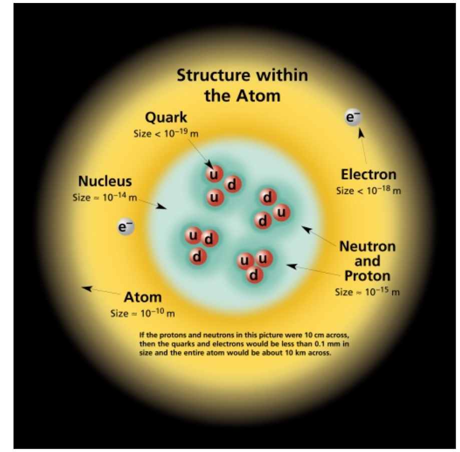


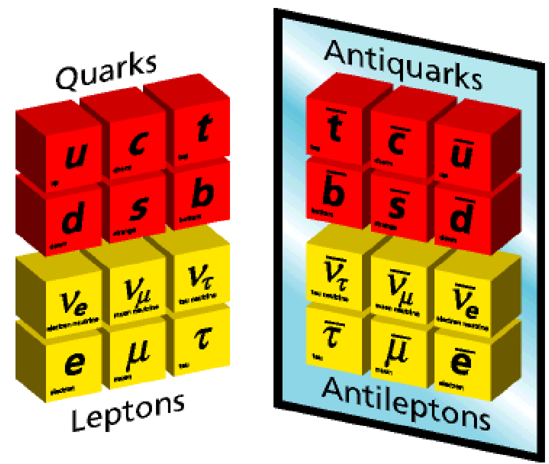


The proton does not only consist of three quarks ***(blue)*** being held together by gluons ***(springs)***, but is a sizzling place of gluons and pairs of quarks and antiquarks ***(green)*** interacting with each other.

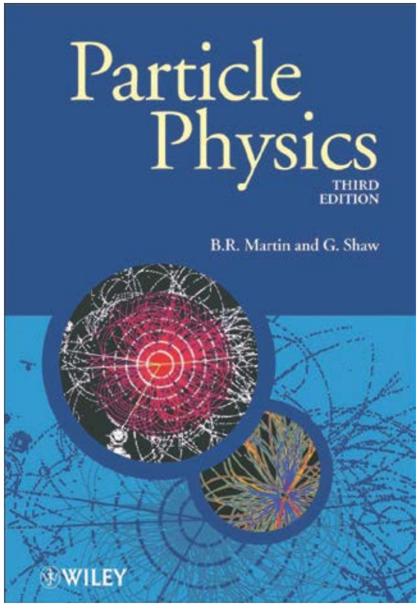
Tentative outline of Particle Physics

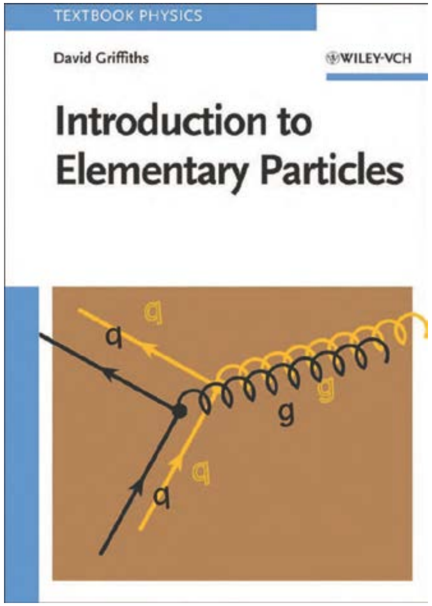
- **Introduction**
  - 100 years of particle physics
- **Basic Concepts**
  - Forces of nature
  - Standard model chart
  - Lepton and Baryon numbers
  - Units and dimensions
  - Cross section and decay rates
- **Feynman Diagrams**
  - exchange of photons
  - exchange of massive bosons
  - Yukawa potential
  - 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**





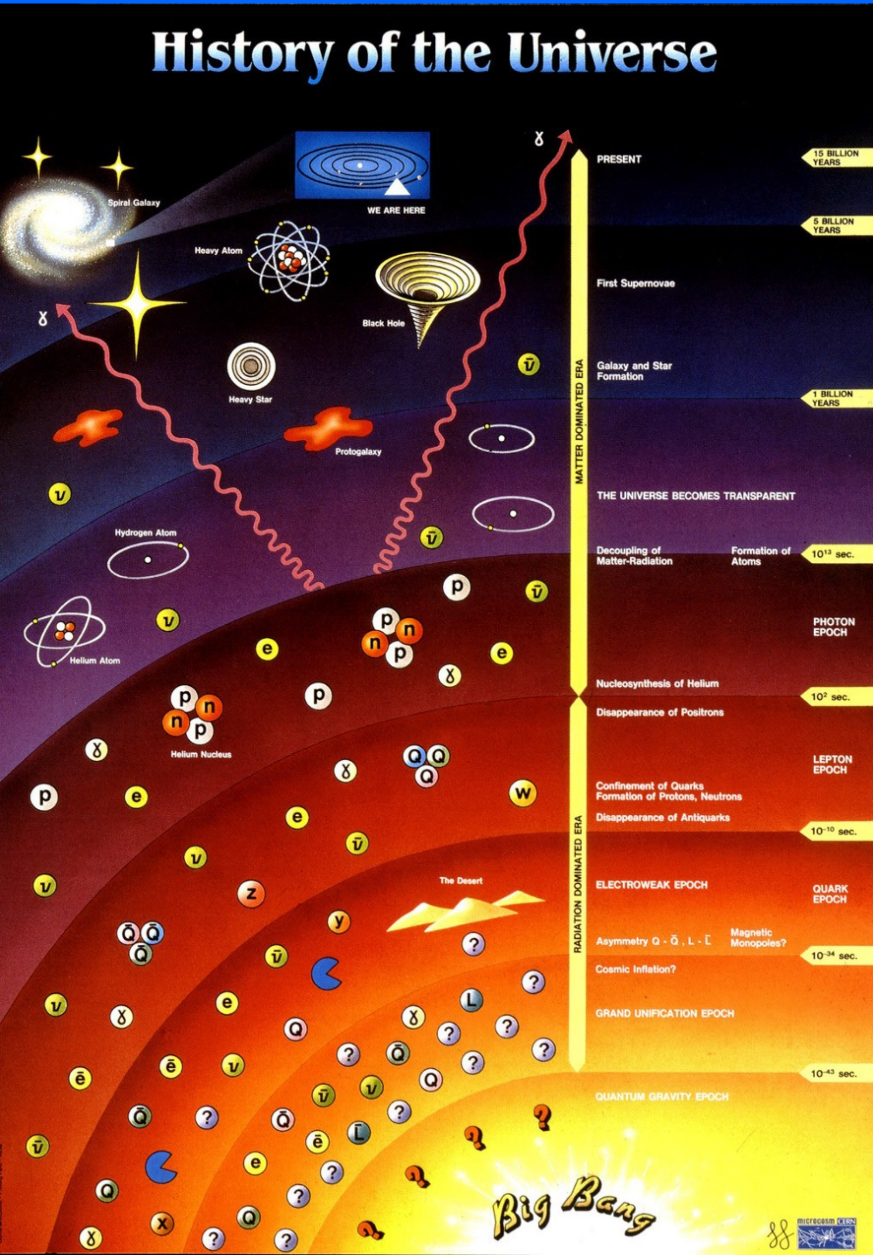
Literature





❖ Recommended Textbook

Particle Physics

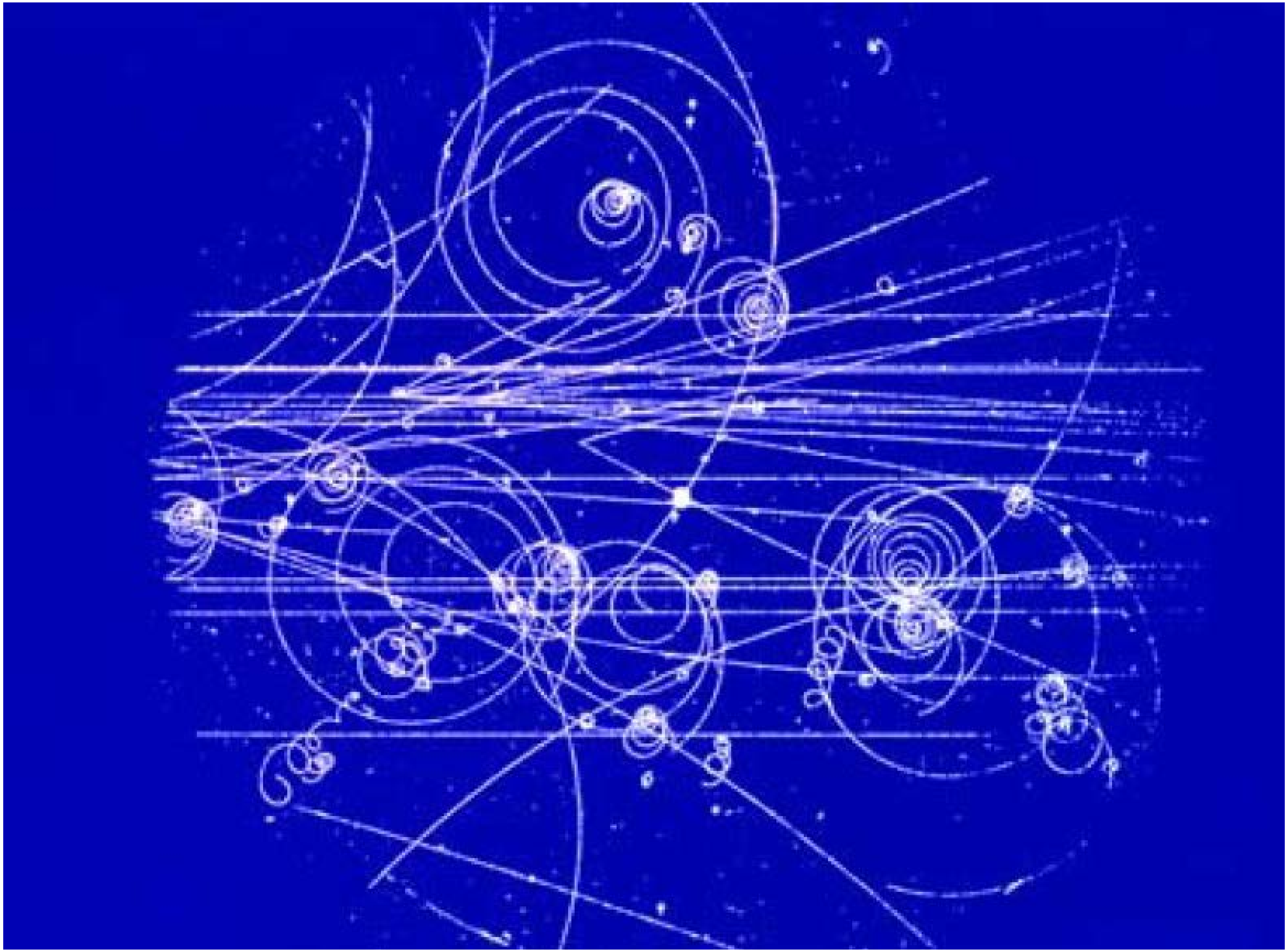


era of gravitation

$10^{13}\ s$

era of particle physics

100 years of particle physics

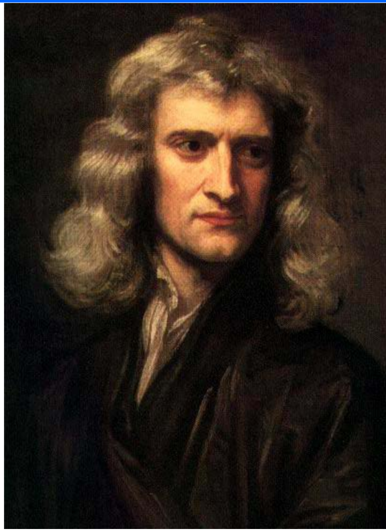


Corpuscular Theory of Light

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 …



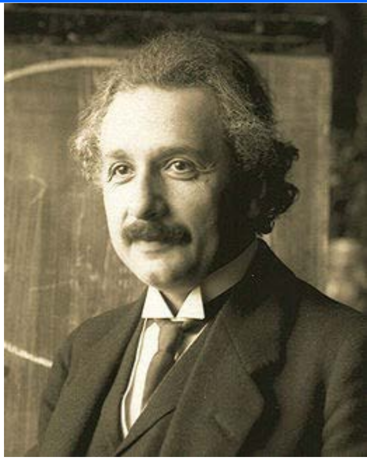
Isaac Newton
1643-1727

Christiaan Huygens
1629-1695

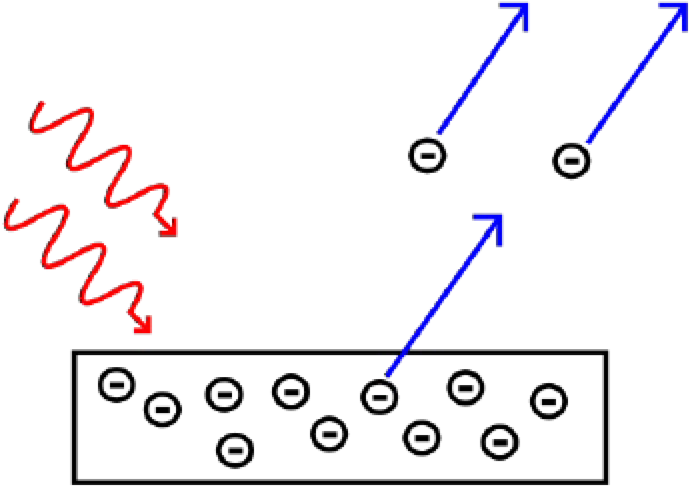
Photoelectric Effect

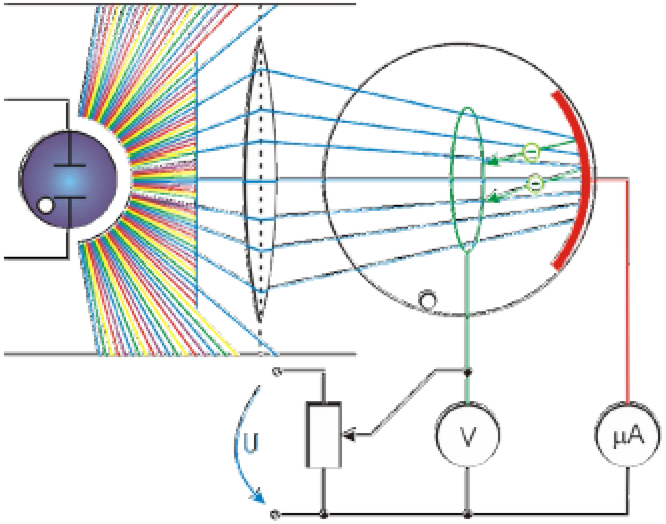
❖ **Observation:** 1836 Becquerel
Metal absorbs light and emits electrons →
Maximum energy of electrons independent on intensity (number of photons)

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

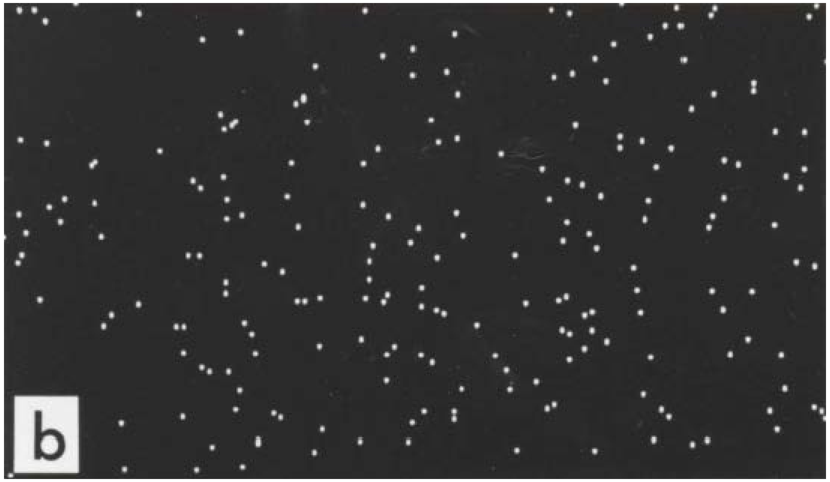


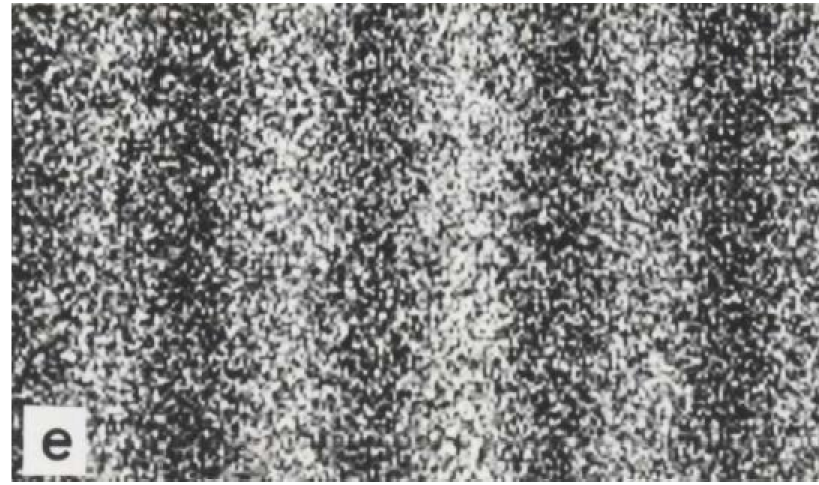
Albert Einstein
1879-1955

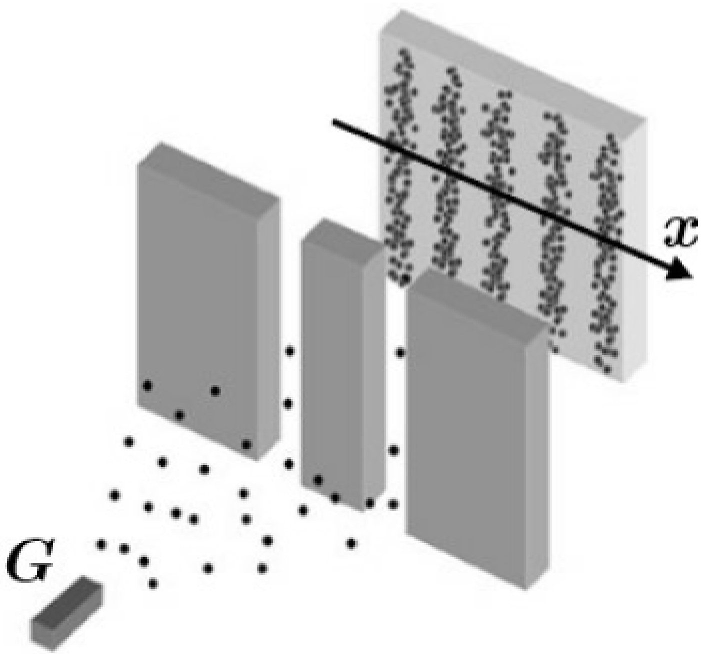




Double Slit with Electrons







Electron (particles) have wavelength

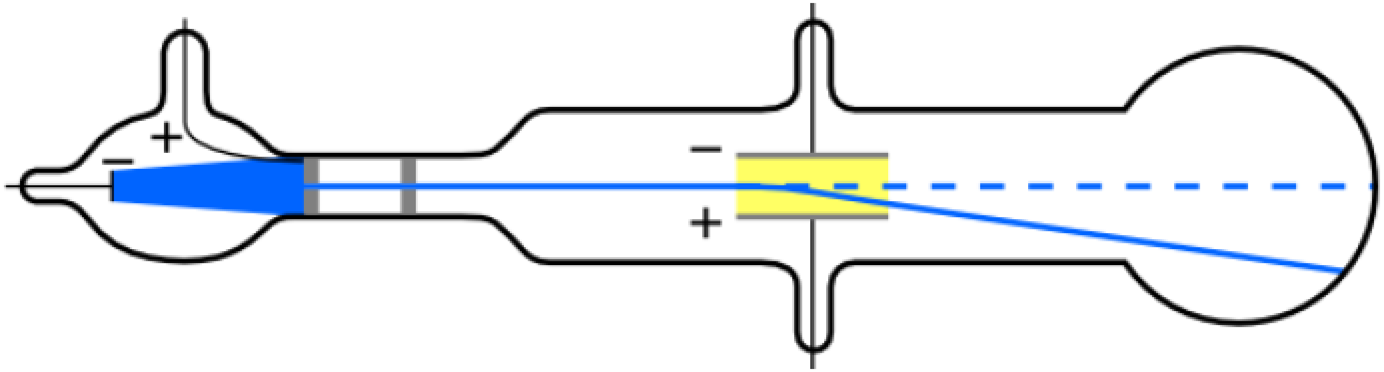
De Broglie wavelength:

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

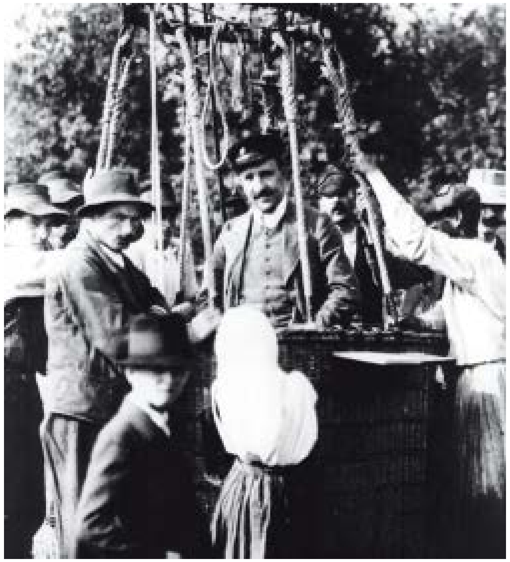
The Electron

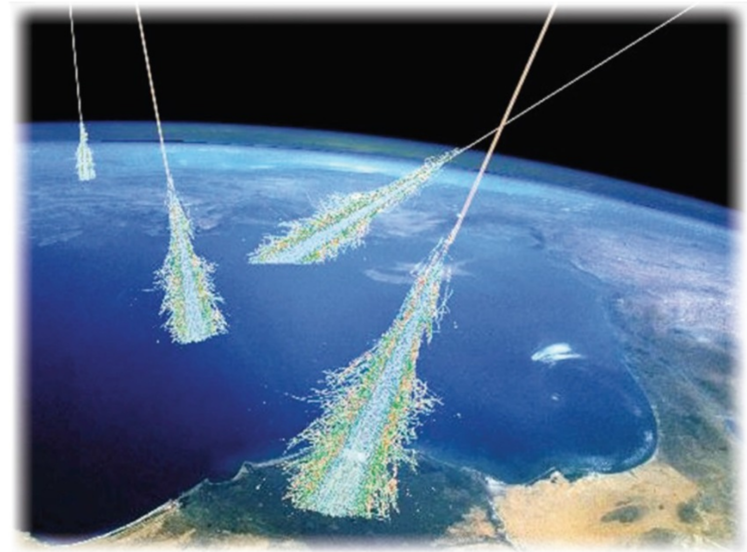
- **Observation:** 1897 (Nobel Prize 1906)
  - Constituents of cathode rays deflected by electric field
  - Constituents of cathode rays deflected by magnetic field + heating of thermal junction → first mass/charge ratio
  - Higher precision of mass/charge from comparing deflection by electric and magnetic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

Joseph J. Thomson
1856-1940

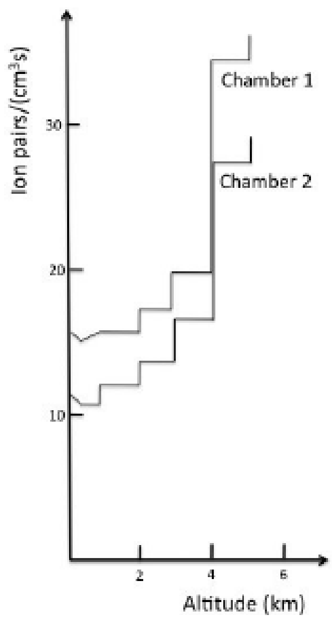


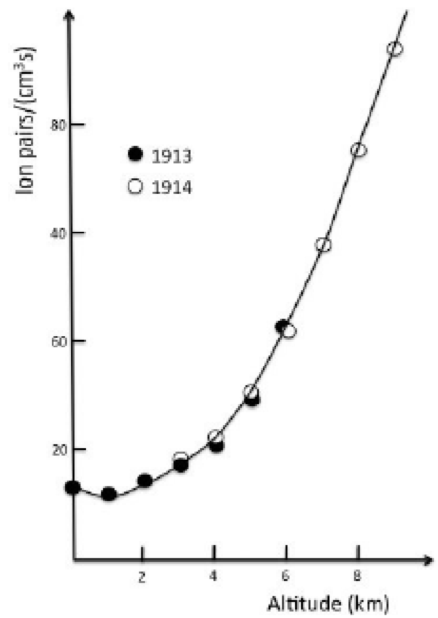
Ionization Measurements





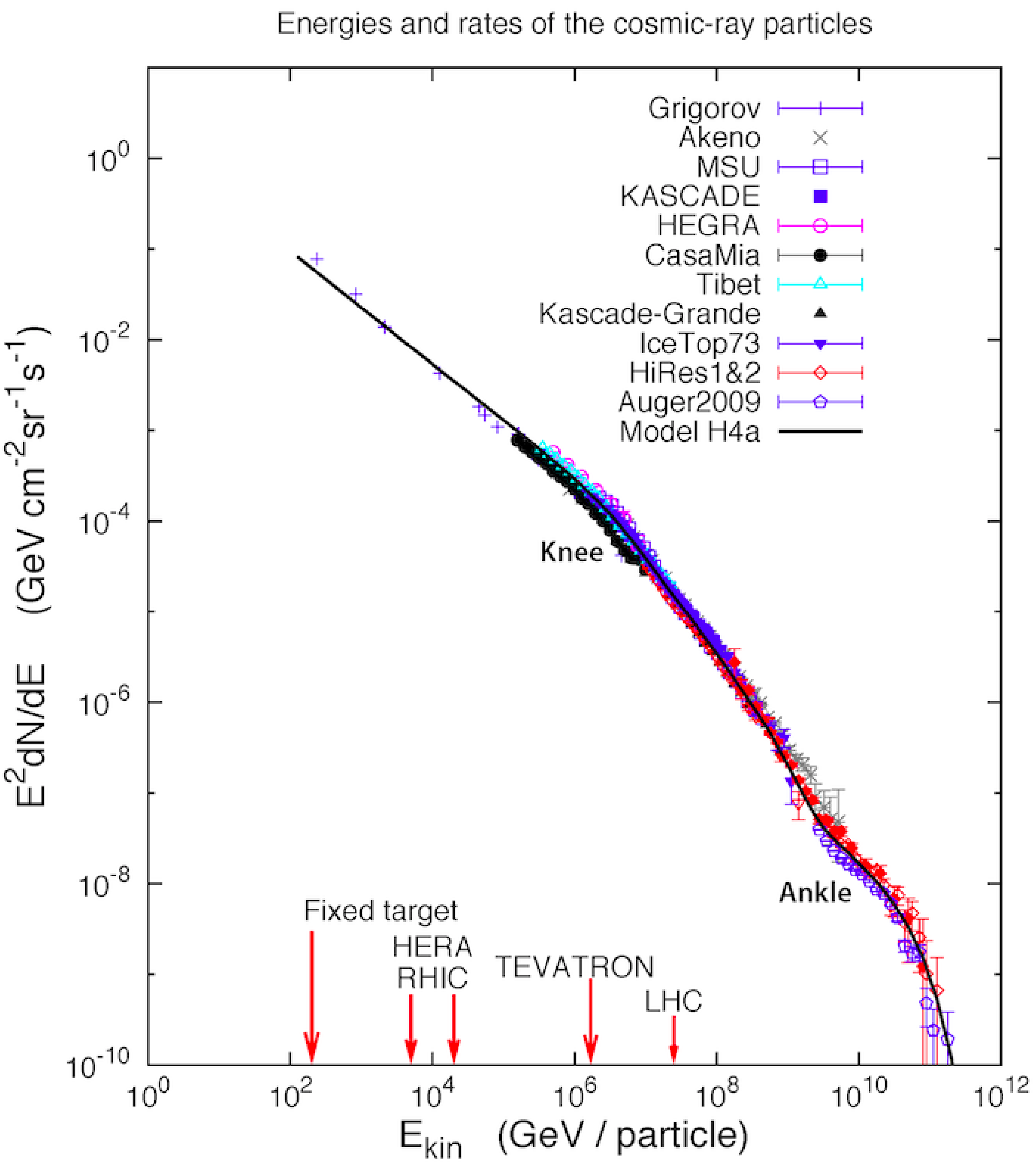
Victor Hess (1912)
discovery of cosmic showers





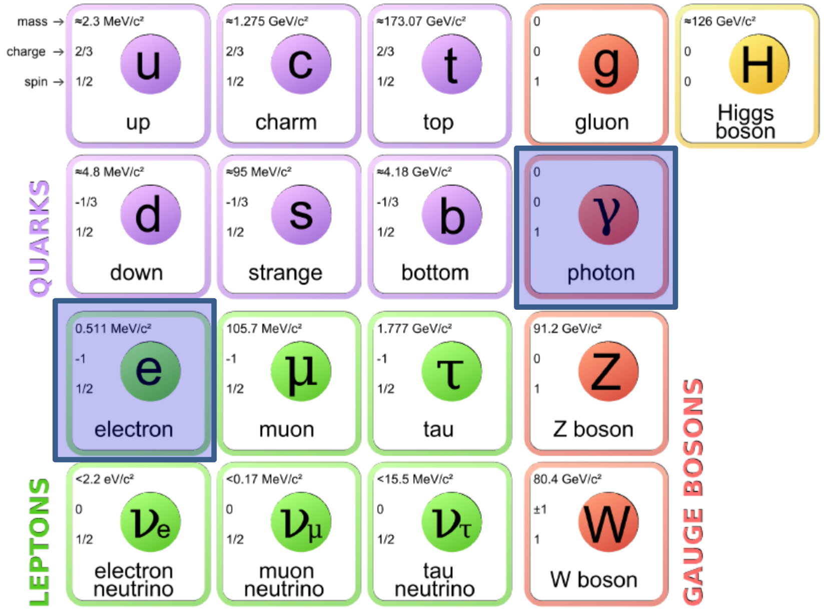
Nobel Prize 1936

The Cosmic Accelerator



1912 ~100 years 2017

- electron
- photons
- nuclei (protons)



1912 ~100 years → 2017

- electron
- photons
- nuclei (protons)

Standard Model Lagrangian

1

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\frac{1}{2}ig_s^2(\bar q^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar G^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar G^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$

2

$$M^2 W^+_\mu W^-_\mu - \frac12\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac12\partial_\mu A_\nu\partial_\mu A_\nu - \frac12\partial_\mu H\partial_\mu H -$$
$$\frac12 m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \frac12\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} +$$
$$\frac{2M}{g}H + \frac12(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu -$$
$$W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu -$$
$$W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac12 g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\frac12 g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$
$$g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$
$$\frac18 g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] -$$
$$gMW^+_\mu W^-_\mu H - \frac12 g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac12 ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$
$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac12 g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu H)] + \frac12 g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$
$$igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac14 g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$
$$\frac14 g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2+(\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-] - \frac12 g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) - \frac12 ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac12 g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \frac12 ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar e^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar\nu^\lambda\gamma\partial\nu^\lambda - \bar u^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j -$$

3

$$\bar d^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar e^\lambda\gamma^\mu e^\lambda) + \frac23(\bar u^\lambda_j\gamma^\mu u^\lambda_j) - \frac13(\bar d^\lambda_j\gamma^\mu d^\lambda_j)] +$$
$$\frac{ig}{4c_w}Z^0_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar u^\lambda_j\gamma^\mu(\frac43 s_w^2 -$$
$$1-\gamma^5)u^\lambda_j) + (\bar d^\lambda_j\gamma^\mu(1 - \frac83 s_w^2 - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt2}W^+_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) +$$
$$(\bar u^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt2}W^-_\mu[(\bar e^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+$$
$$\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt2}\frac{m_e^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar e^\lambda(1+\gamma^5)\nu^\lambda)] -$$

4

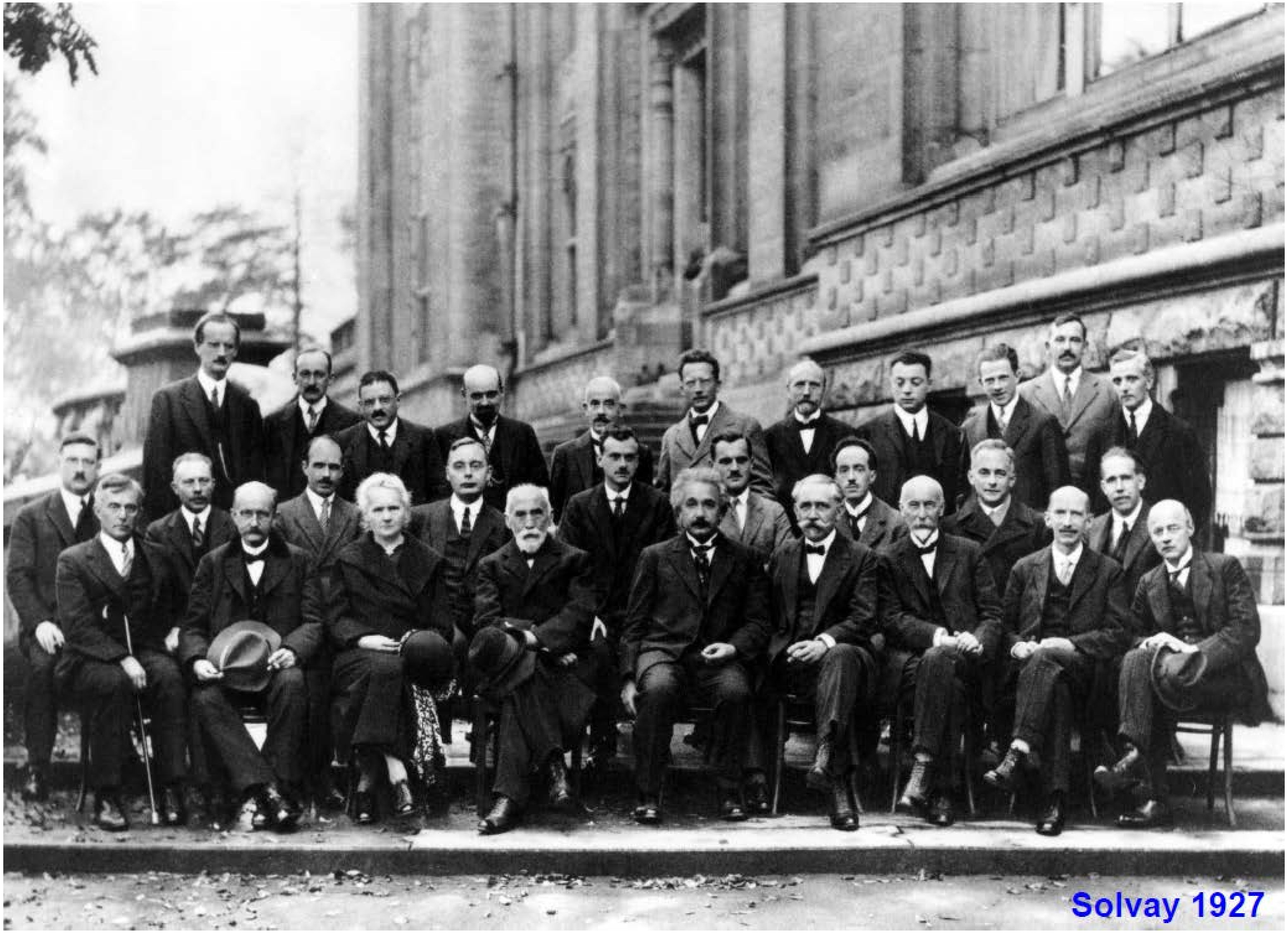
$$\frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar e^\lambda e^\lambda) + i\phi^0(\bar e^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt2}\phi^+[-m_d^\kappa(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$
$$m_u^\lambda(\bar u^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt2}\phi^-[m_d^\lambda(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1-$$
$$\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar u^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar d^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar u^\lambda_j\gamma^5 u^\lambda_j) -$$
$$\frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j) + \bar X^+(\partial^2 - M^2)X^+ + \bar X^-(\partial^2 - M^2)X^- + \bar X^0(\partial^2 -$$

5

$$\frac{M^2}{c_w^2})X^0 + \bar Y\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar X^0 X^- - \partial_\mu\bar X^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar Y X^- -$$
$$\partial_\mu\bar X^+ Y) + igc_w W^-_\mu(\partial_\mu\bar X^- X^0 - \partial_\mu\bar X^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar X^- Y -$$
$$\partial_\mu\bar Y X^+) + igc_w Z^0_\mu(\partial_\mu\bar X^+ X^+ - \partial_\mu\bar X^- X^-) + igs_w A_\mu(\partial_\mu\bar X^+ X^+ -$$
$$\partial_\mu\bar X^- X^-) - \frac12 gM[\bar X^+X^+H + \bar X^-X^-H + \frac{1}{c_w^2}\bar X^0X^0H] +$$
$$\frac{1-2c_w^2}{2c_w}igM[\bar X^+X^0\phi^+ - \bar X^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-] +$$
$$igMs_w[\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-] + \frac12 igM[\bar X^+X^+\phi^0 - \bar X^-X^-\phi^0]$$

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



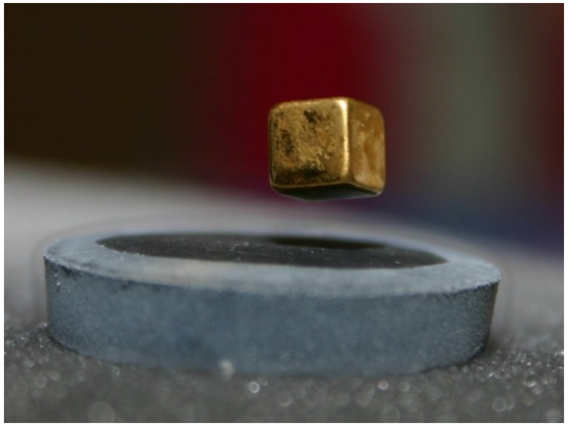
A. Piccard, E. Henriot, P. Ehrenfest, E. Herzen, Th. de Donder, E. Schrödinger, J.E. Verschaffelt, W. Pauli, W. Heisenberg, R.H. Fowler, L. Brillouin
P. Debye, M. Knudsen, W.L. Bragg, H.A. Kramers, P.A.M. Dirac, A.H. Compton, L. de Broglie, M. Born, N. Bohr,
I. Langmuir, M. Planck, M. Curie, H.A. Lorentz, 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***

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



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

Satyendranath Bose

Enrico Fermi

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:	$E \to i\hbar\frac{\partial}{\partial t} \quad and \quad \vec{p} \to -i\hbar\vec{\nabla}$	$E \to i\frac{\partial}{\partial t} \quad and \quad \vec{p} \to -i\vec{\nabla}$
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

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 $\longrightarrow$ ***-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:	$E \to i\hbar\frac{\partial}{\partial t}$ *and* $\vec{p} \to -i\hbar\vec{\nabla}$	$E \to i\frac{\partial}{\partial t}$ *and* $\vec{p} \to -i\vec{\nabla}$
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

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

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

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:

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

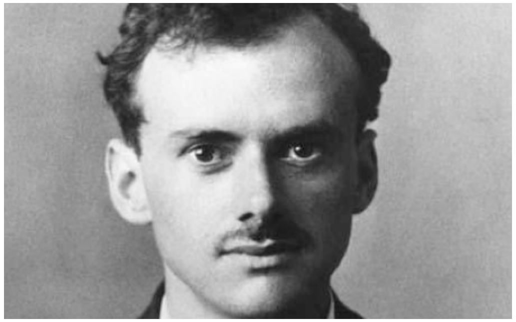
The factor ***i*** is introduced to make the density real

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

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



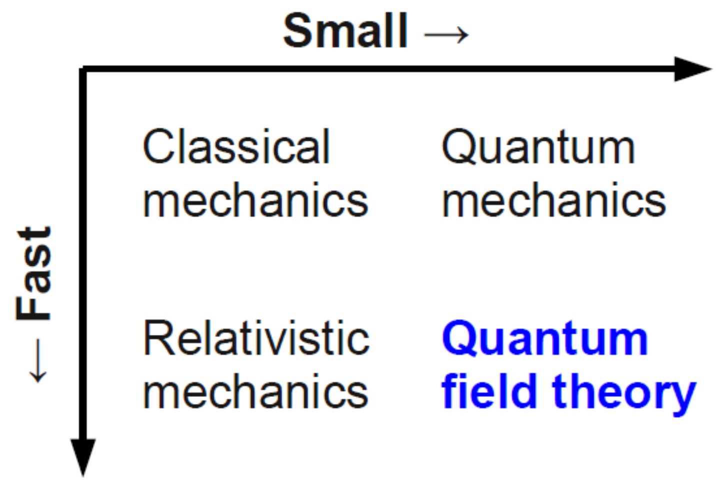
Paul Dirac 1902-1984

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. αk 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

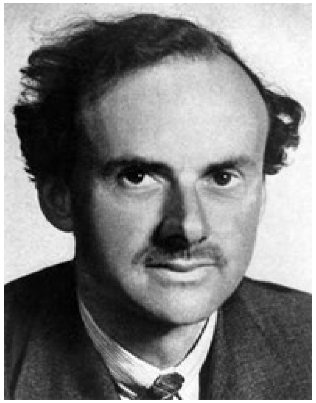


- **First major achievement:** Dirac's equation for free electrons (and positrons)

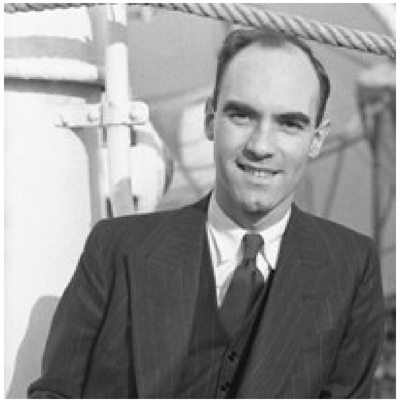
$$E^2 = (mc^2)^2 + (pc)^2$$

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

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

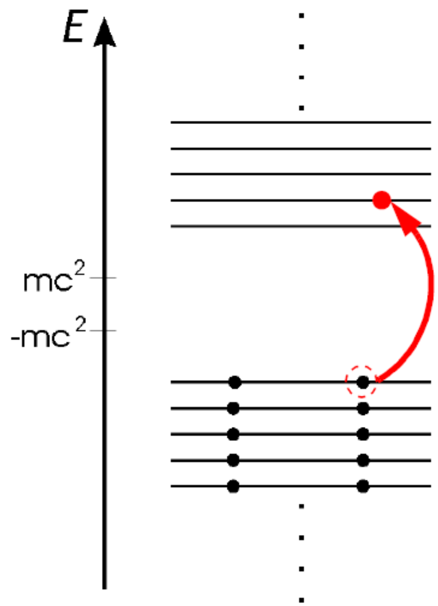


Paul Dirac
1902-1984
Nobel Prize 1933



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.

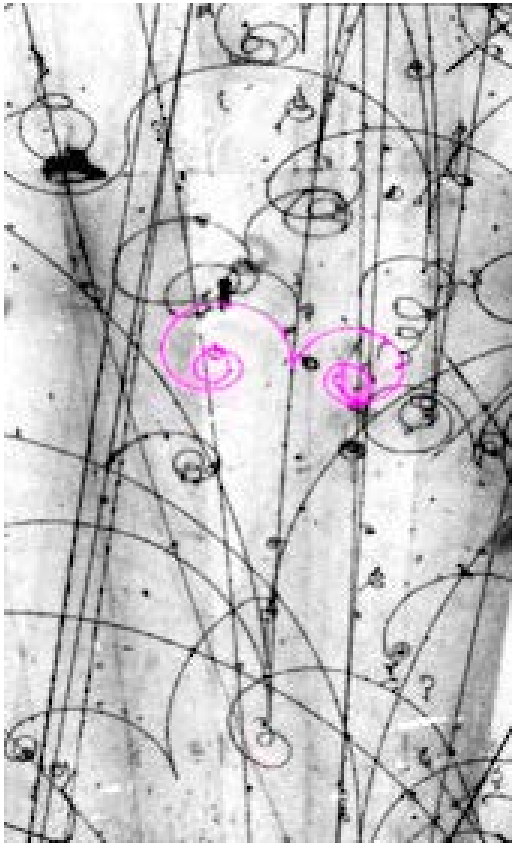
"negative" energy → antiparticles

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)

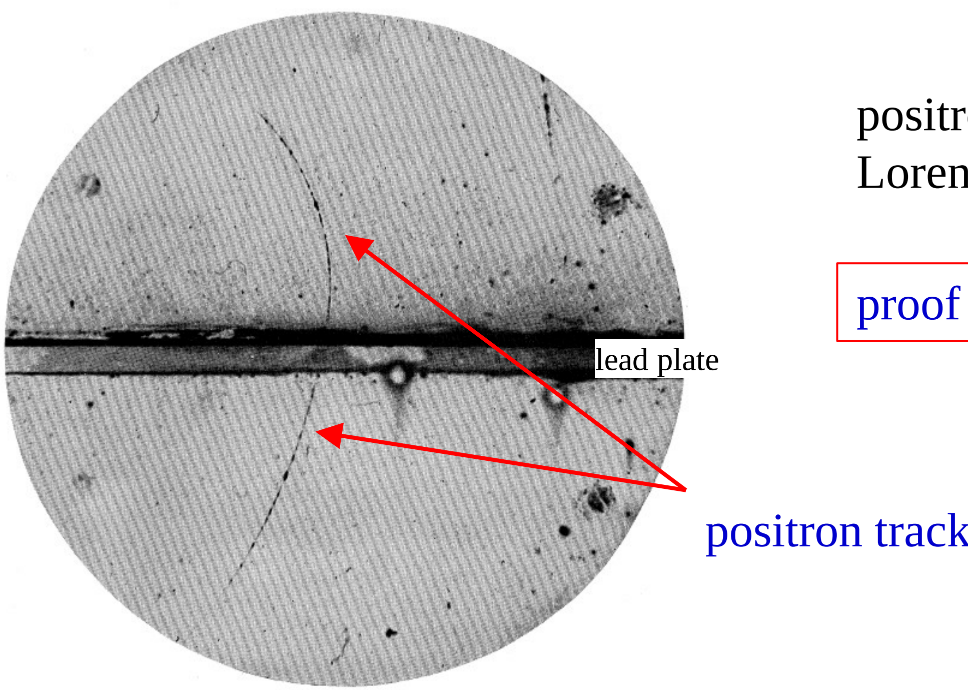


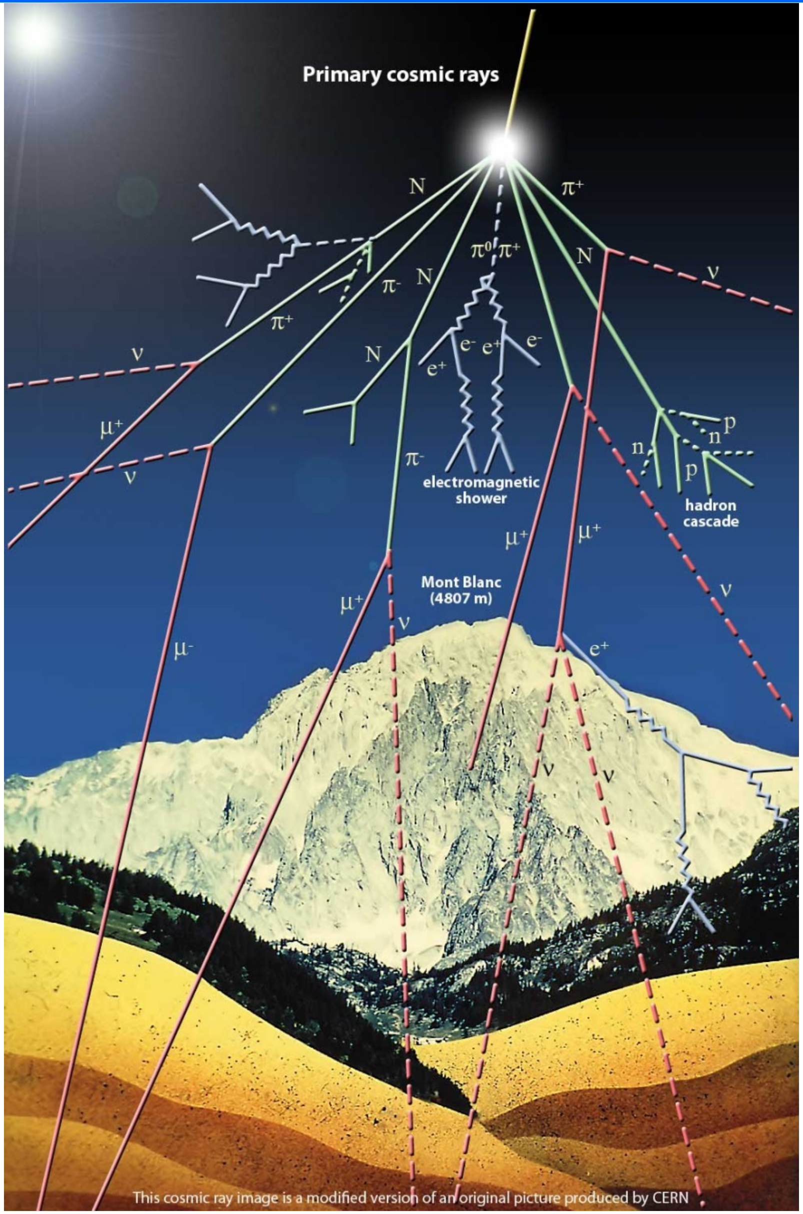
FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

positrons are bent due to
Lorentz force in magnetic field

proof of existence of antiparticles

Carl D. Anderson; Nobel Prize 1936

Muon Discovery (1936)



Carl D. Anderson; Nobel Prize 1936

Muon-Lepton discovery in cosmic rays by

Carl D. Anderson

+

Seth Nedermeyer

mass: m_μ ~ 100 MeV

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

Prediction of the Pion

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"

Hideki Yukawa
1907-1981

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.

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

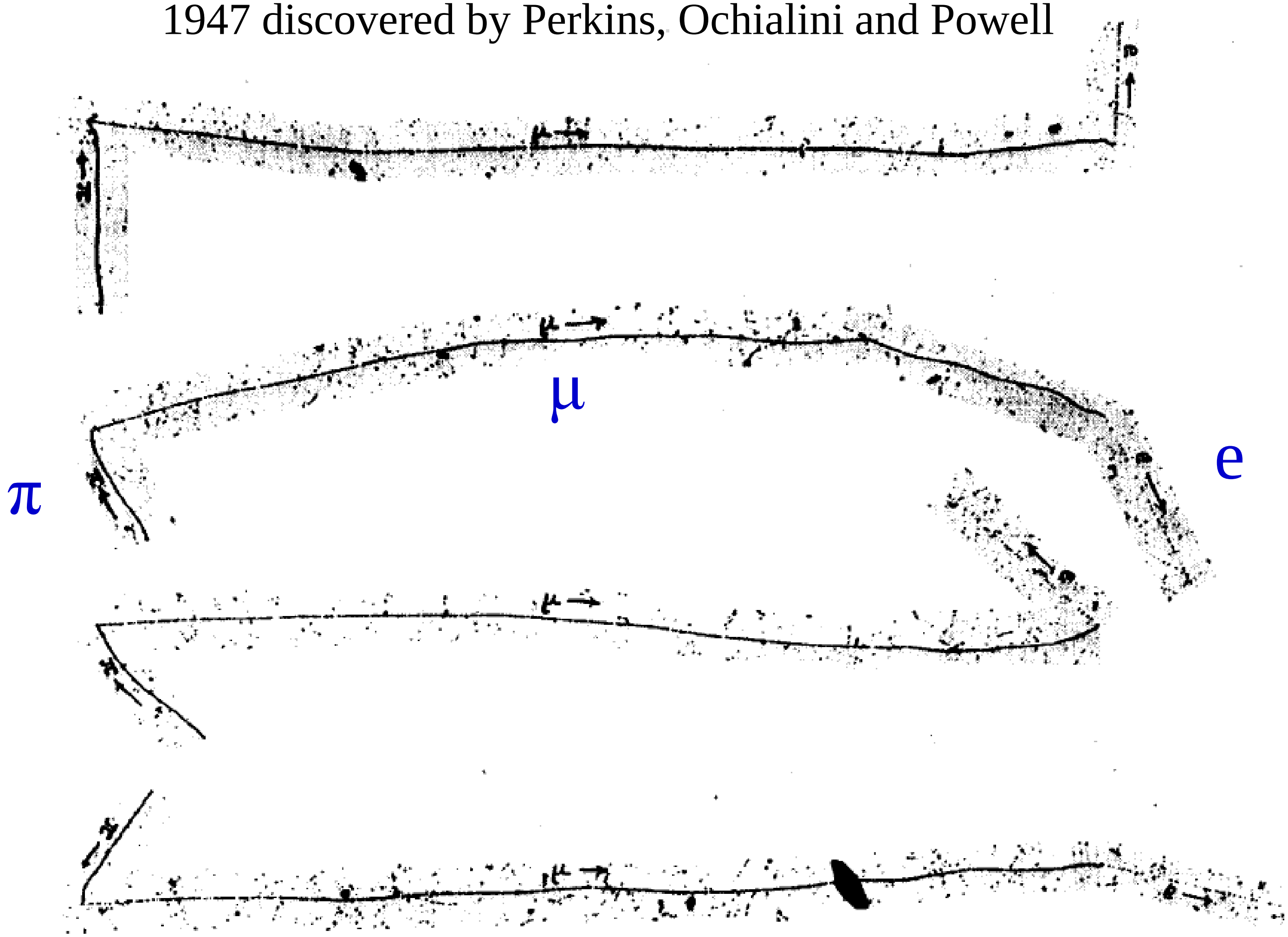
$$\boxed{\Delta x = \hbar c / Mc^2}$$

- 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 the Pion

1947 discovered by Perkins, Ochialini and Powell

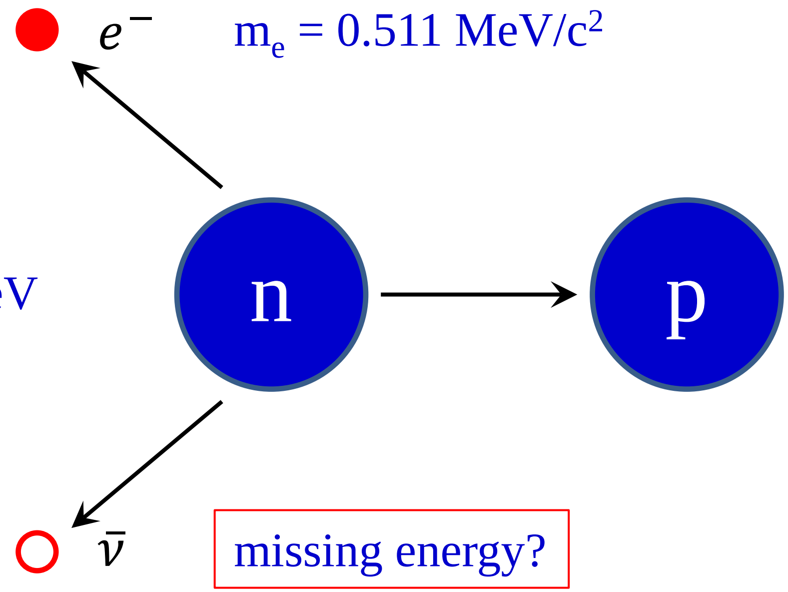


First observed pions: a π^+ stops in the emulsion and decays to a μ^+ and ν_μ, followed by the decay of μ^+.

Powell; Nobel Prize 1950

Beta Decay

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



$m_e = 0.511\ MeV/c^2$

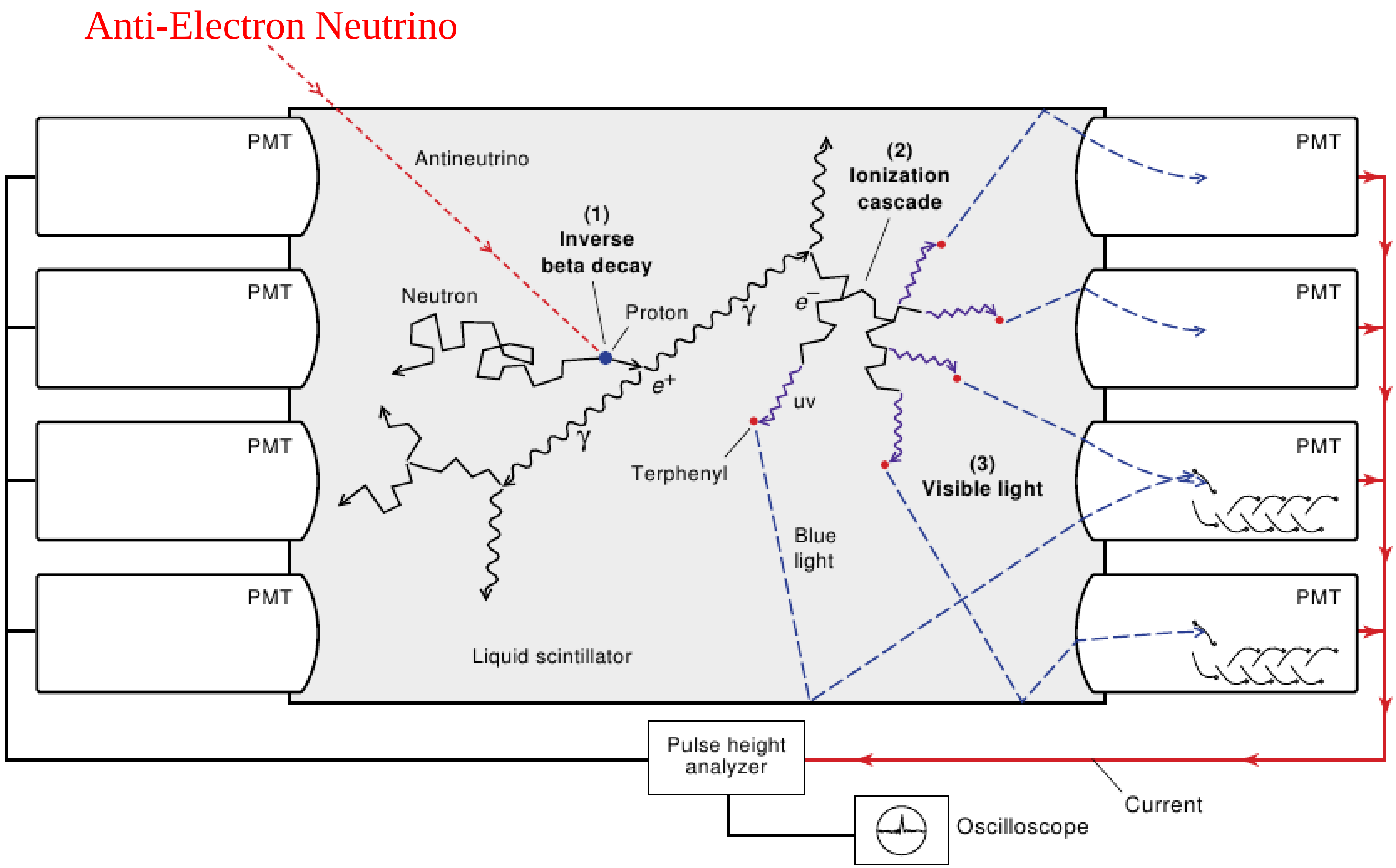
$m_n = 939.565\ MeV$

$m_p = 938.272\ MeV$

missing energy?

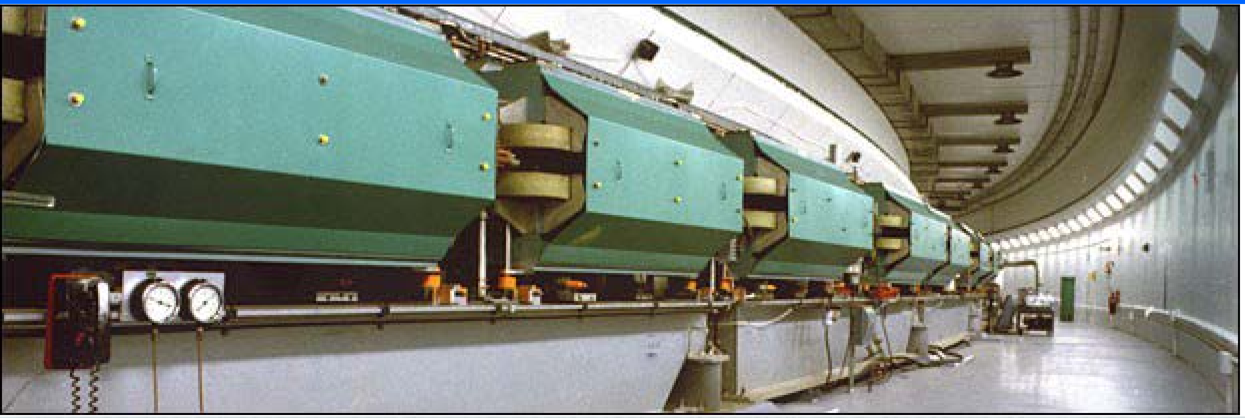
W. Pauli predicted in a letter to E. Fermi the existence of <u>neutrinos</u> (1930)

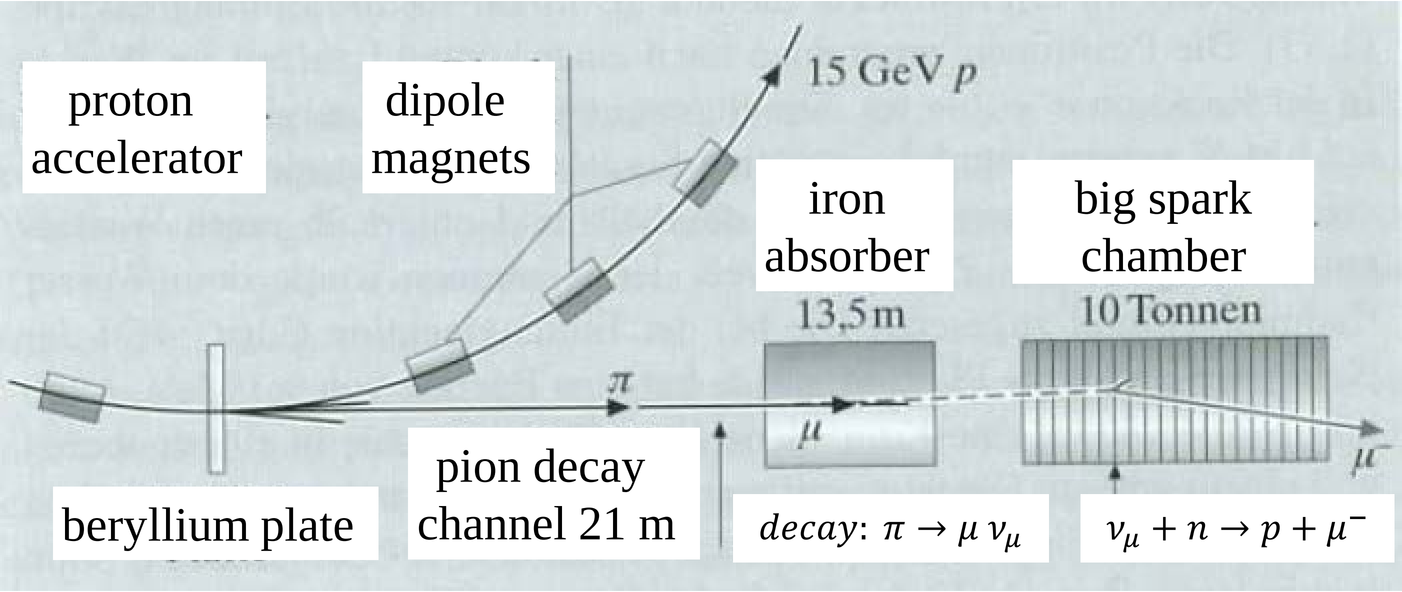
Discovery of the ***electron neutrino*** (Cowan, **Reines**, 1957)



Nobel Prize 1995

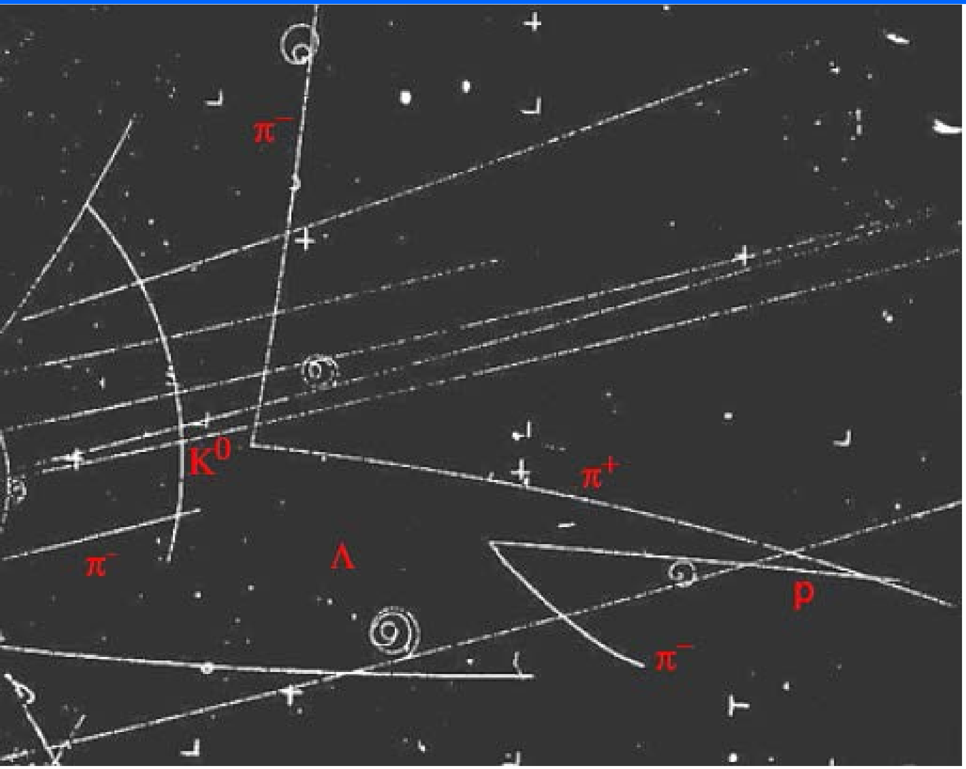
Existence of Muon-Neutrinos



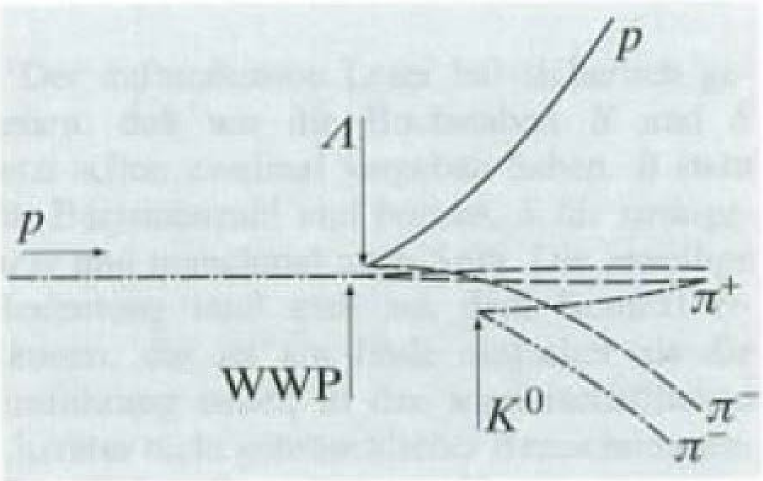


Discovery of the ***muon neutrino*** (Ledermann, Schwartz, Steinberger 1962)

Nobel Prize 1988



A bubble chamber picture of the above reaction



"V-particles"

Production of ***Kaons*** and

K$^+$($u\bar{s}$), K^0 $(d\bar{s}/s\bar{d})$, 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

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:

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

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

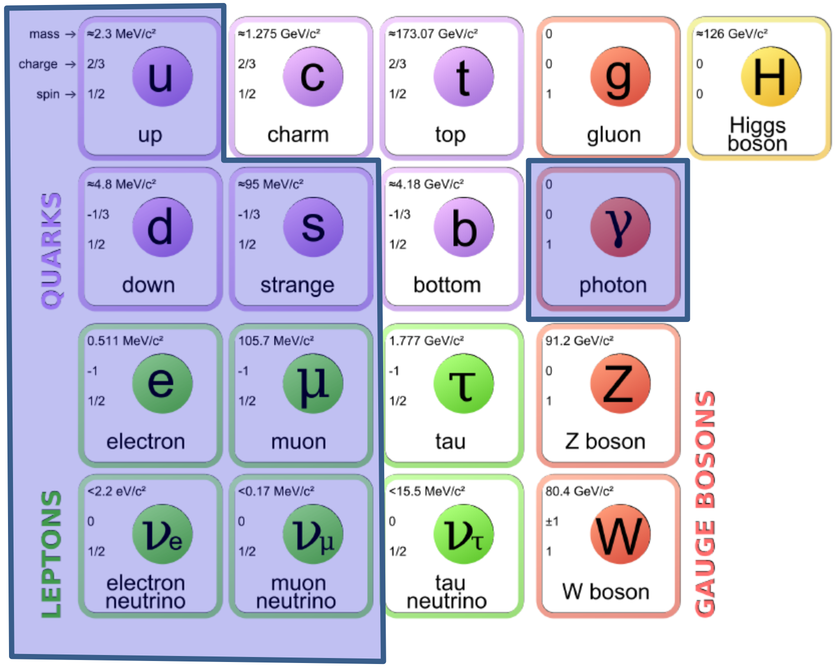
$$\Lambda \rightarrow \pi^- + p \qquad (B=0.64)$$

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

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…

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

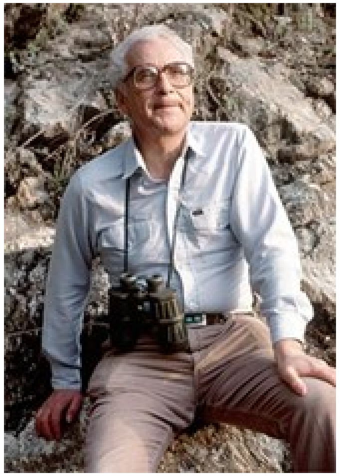
known fermions



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

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

in the year 1964



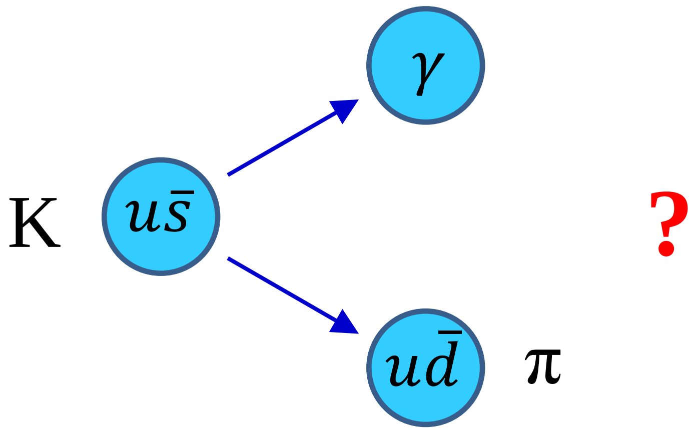
Murray Gell-Mann
1929-

George Zweig
1937-

Nobel Prize 1969

Prediction of the Charm-Quark

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



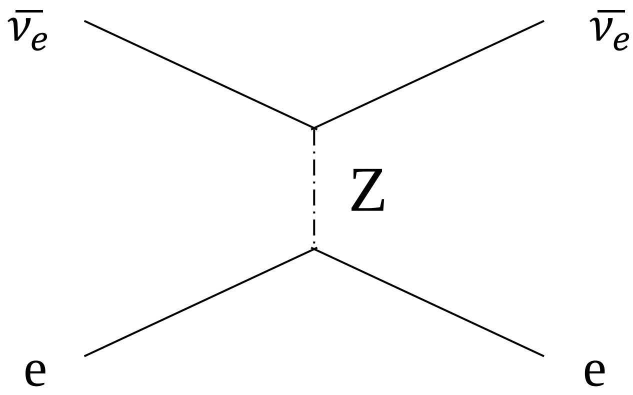
Such a **flavor changing** decay is forbidden if a **fourth quark** exists
(Glashow, Iliopoulos, Maiani)

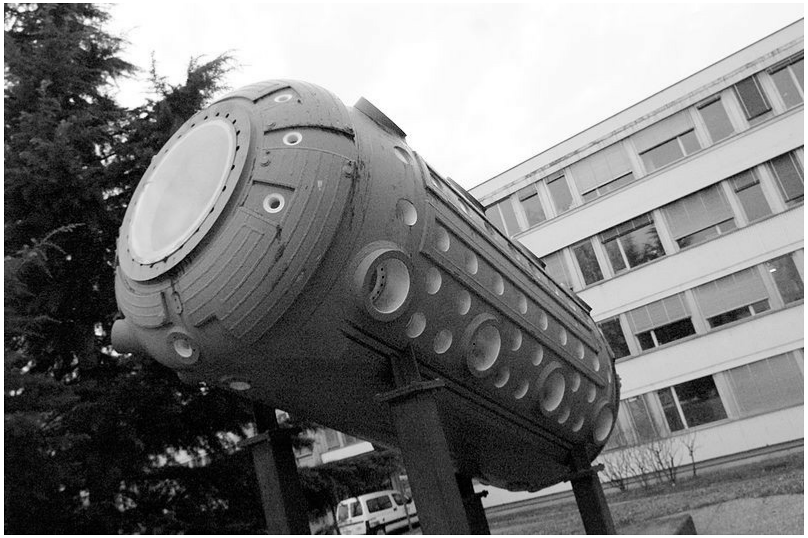
prediction

Note: Kaon and Pion have similar quantum numbers!

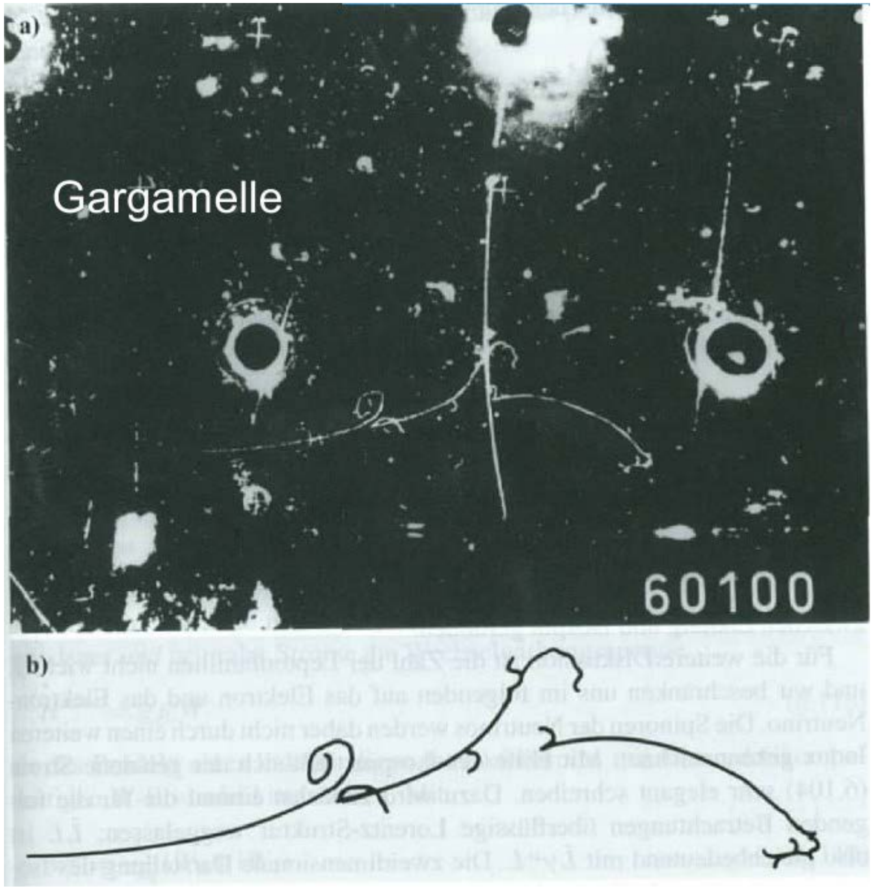
Observation of Neutral Currents

$$\overline{\nu}_e \, e \;\rightarrow\; \overline{\nu}_e \, e$$





Bubble Chamber Gargamelle (1974)



We find interactions without visible incoming or outgoing particle.

Observation of the Charm-Quark

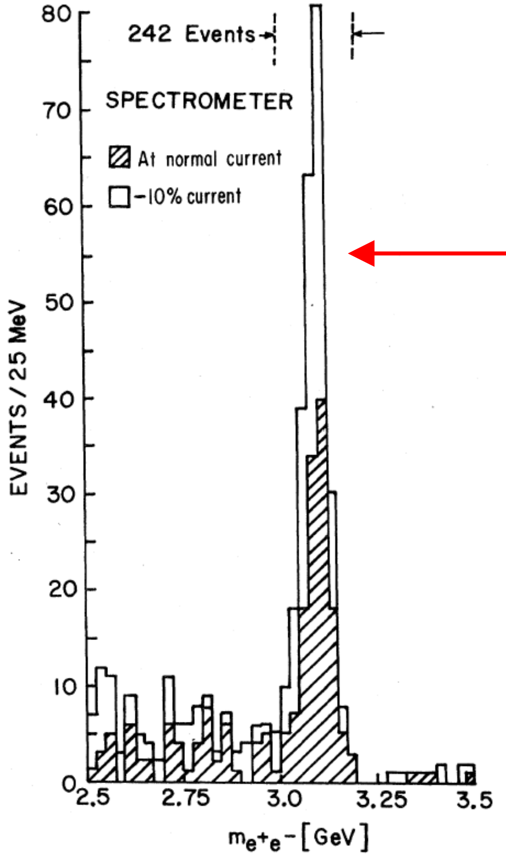


FIG. 2. Mass spectrum showing the existence of *J*. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

$c\bar{c}$

resonance

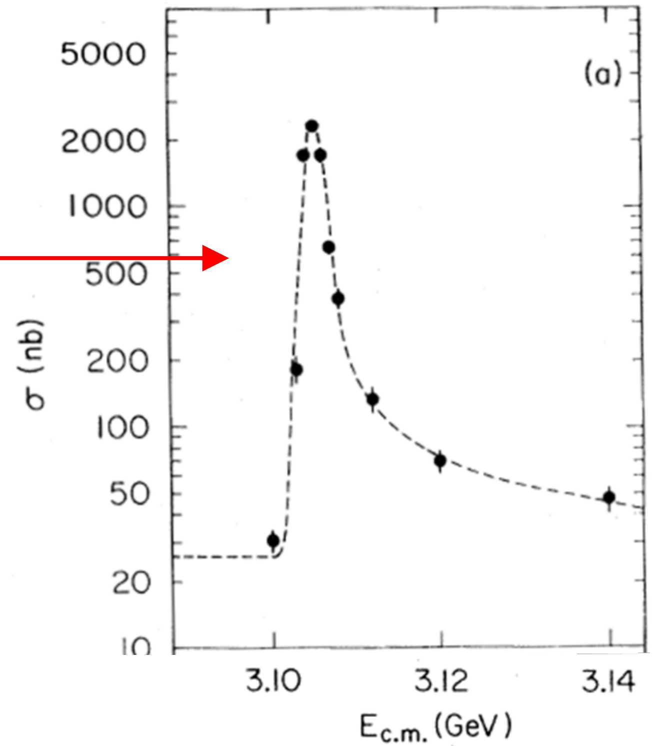


FIG. 1. Cross section versus energy for (a) multi-hadron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^- final states. The curve in (a) is the expected shape of a δ-function resonance folded with the Gaussian energy spread of the beams and including radiative processes. 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:

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

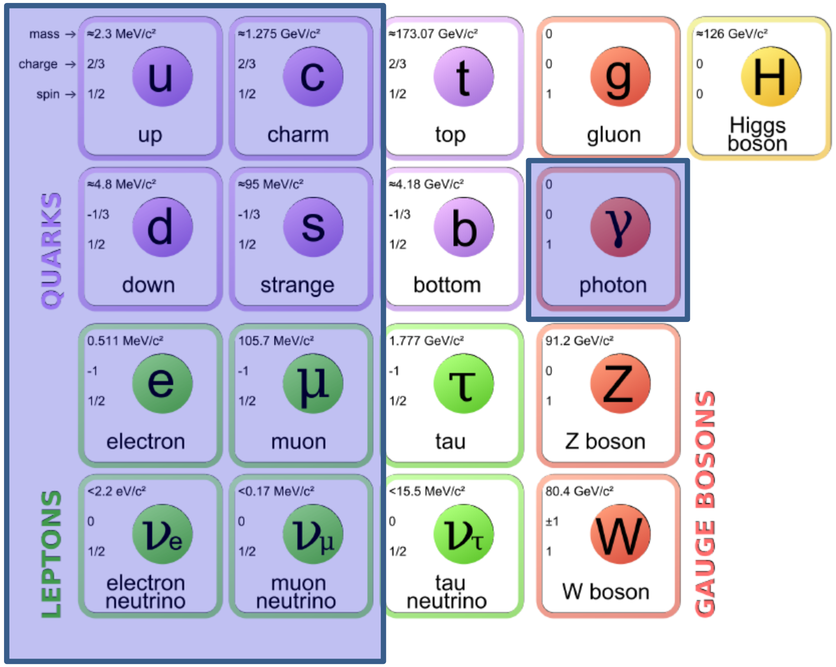
$$D^-(1869) = d\bar{c}, \qquad D^0(1865) = cu$$

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

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

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

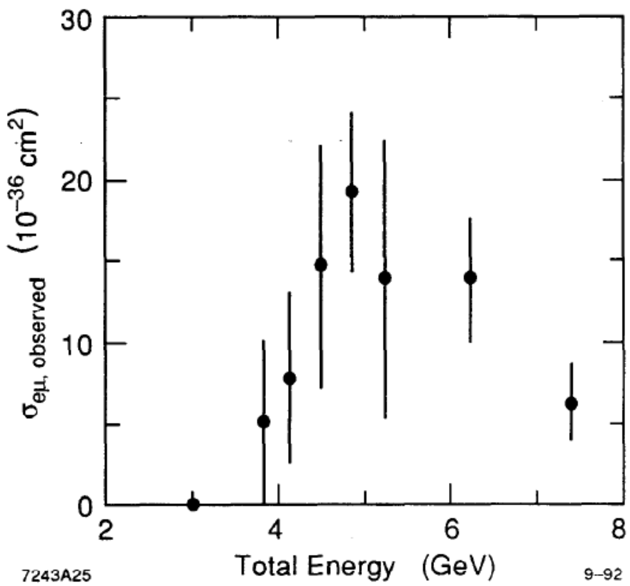


Fig. 4. From Perl *et al.* (1975): the observed cross section for the signature $e\mu$ events from the Mark I experiment at SPEAR. This observed cross section is not corrected for acceptance. There are 86 events with a calculated background of 22 events.

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

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

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

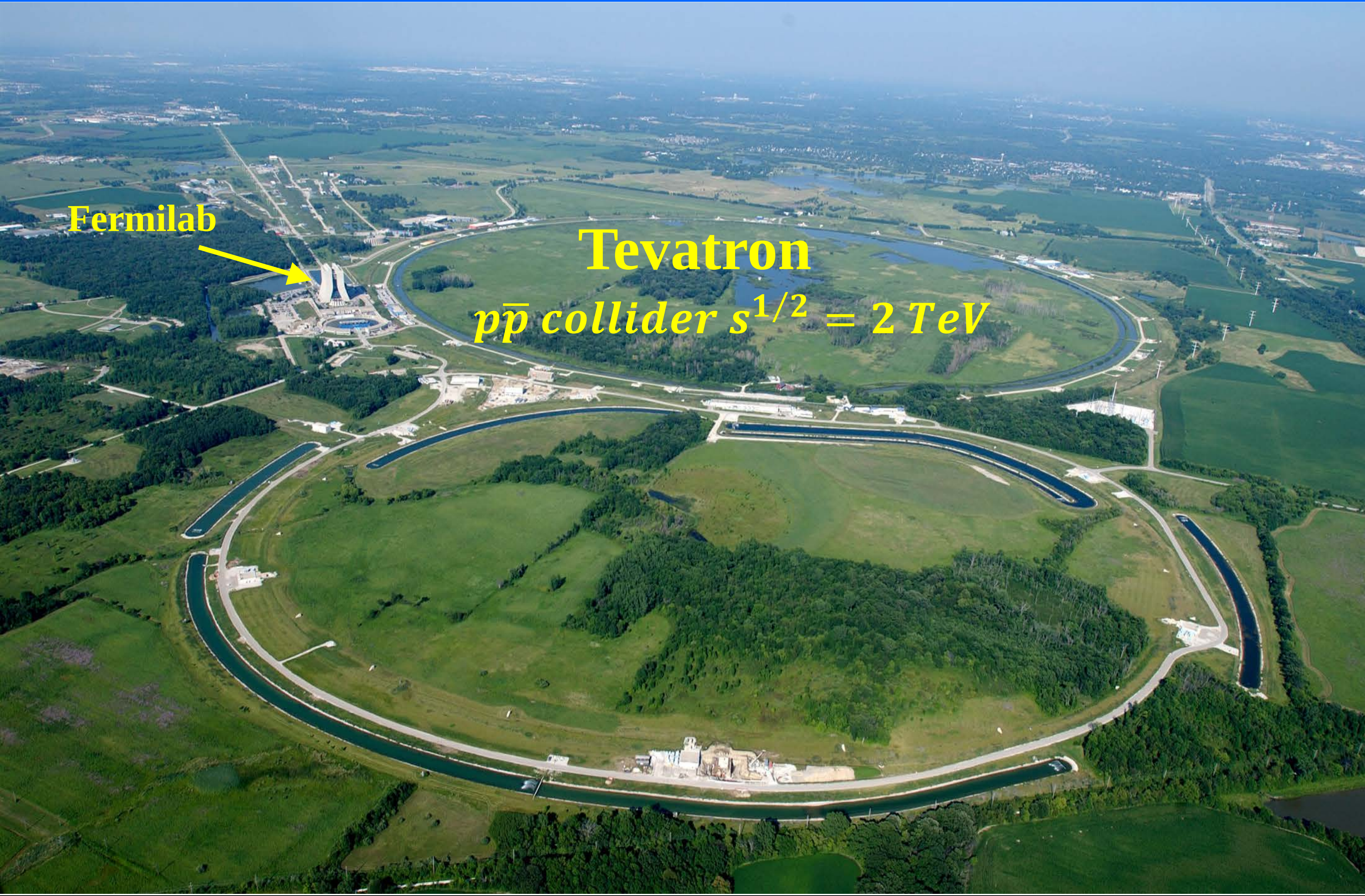
$$\boxed{m_\tau = 1.777\ GeV}$$

discovery of ***tau-lepton***

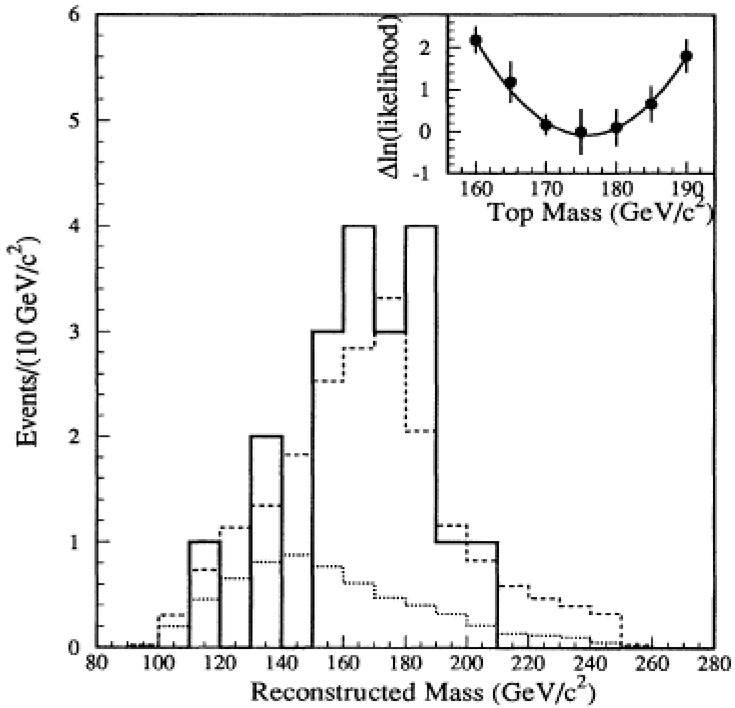
(Reines et al., M. Perl Nobel Prize 1995**)**

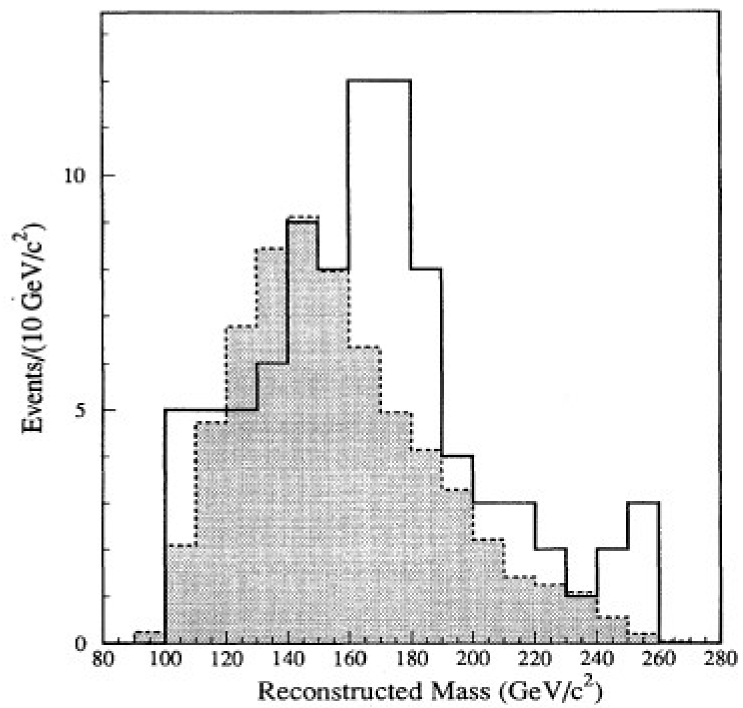
Discovery of the ***Bottom-Quark*** (1977) by **M. Ledermann et al.** Nobel Prize 1988

Top-Quark Discovery at Tevatron



Top-Quark Discovery in 1995





CDF Collaboration

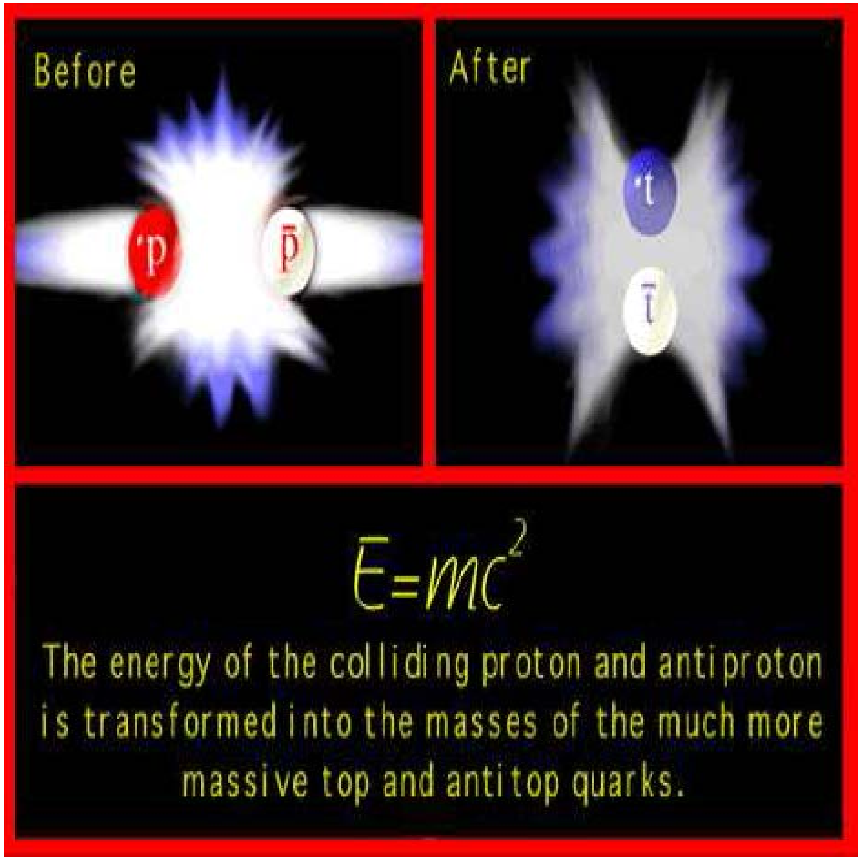
C0 Collaboration

Top-Quark mass ~ 175 GeV

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

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

Top-Quark Discovery in 1995



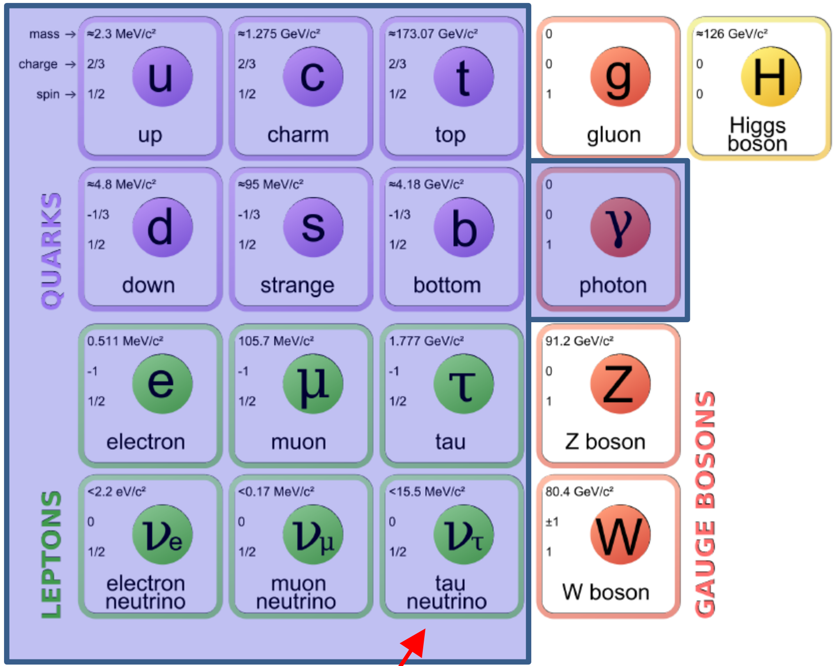
Top-Quark mass ~ 175 GeV

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



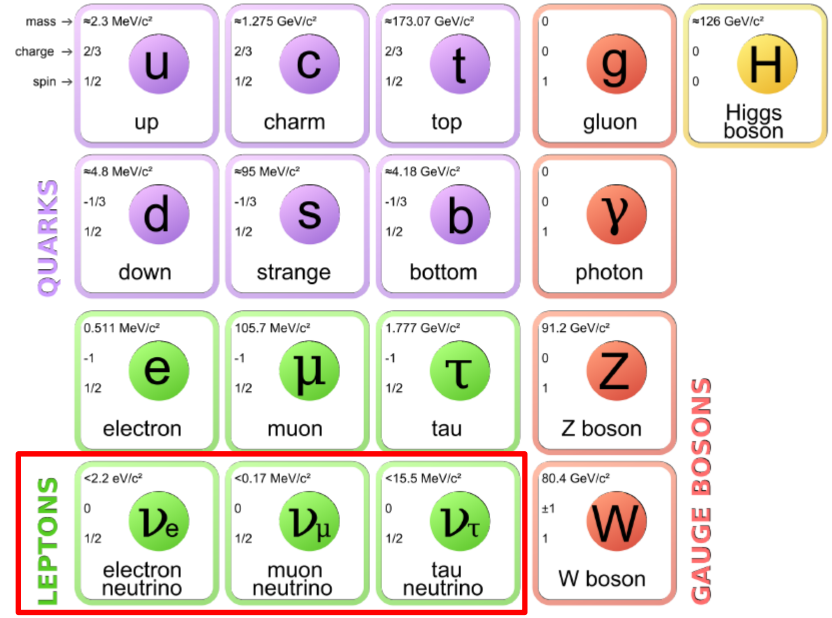
tau-neutrino discovered
in 2000 by Donut experiment

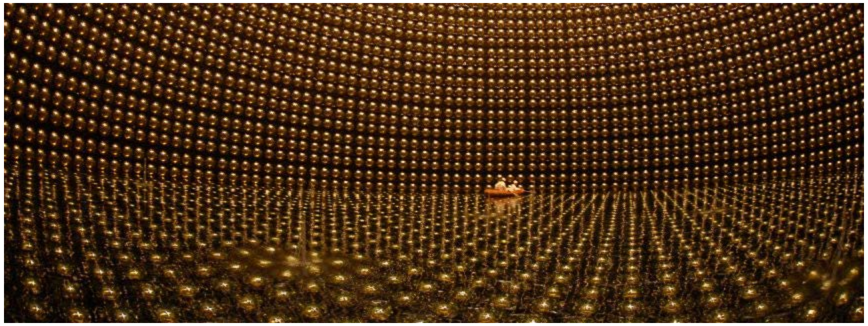
Status in 2002 (~90 years after Hess balloon trip)

Nobel Prize 2015

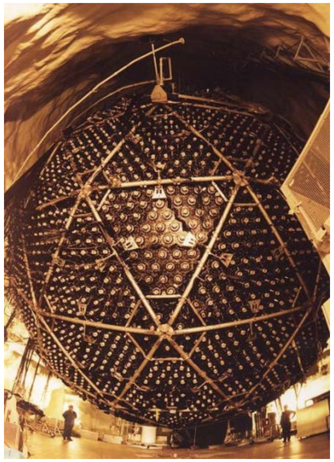
Takaaki Kajita + Arthur B. McDonald

neutrinos have mass!





Super-Kamiokande (1998)



SNO experiment (2001/2)

Discovery of Vector-Bosons

Photons:

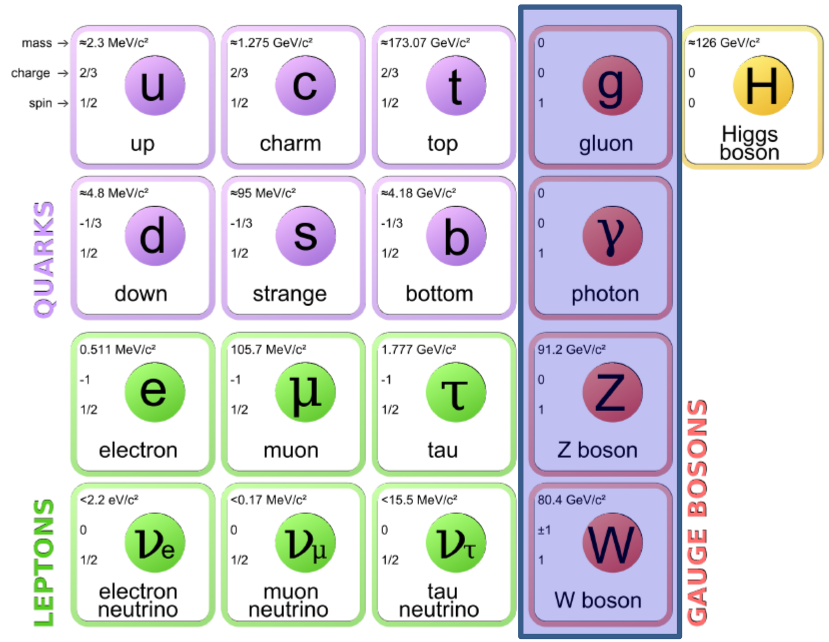
- X-rays (Röntgen 1895) → Nobel Prize 1901
- photo-electric effect (Einstein 1905) → Nobel Prize 1921

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

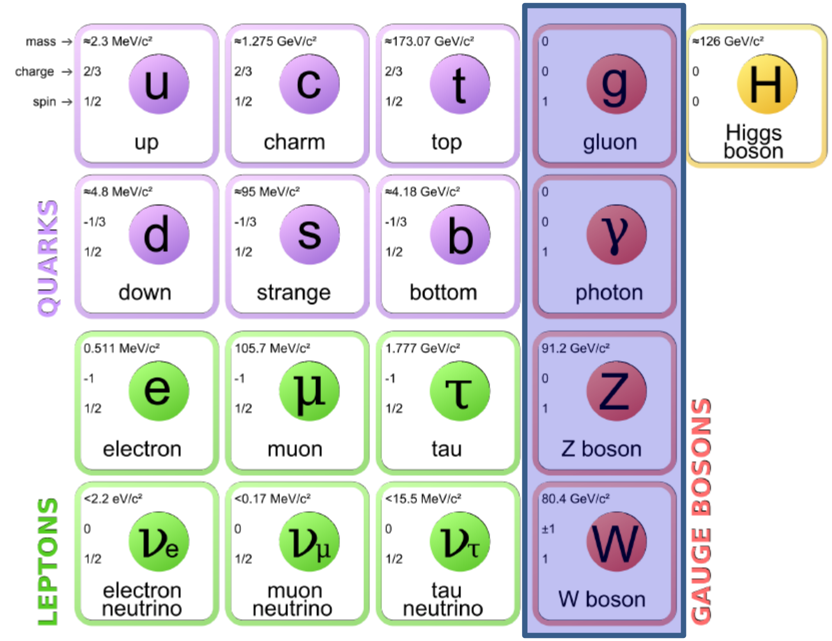


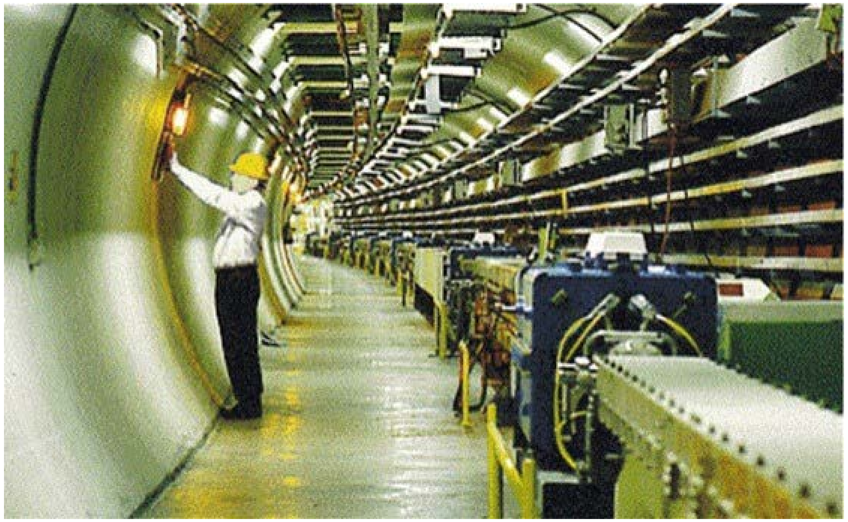
Abdus Salam, Steven Weinberg, Sheldon L. Glashow

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





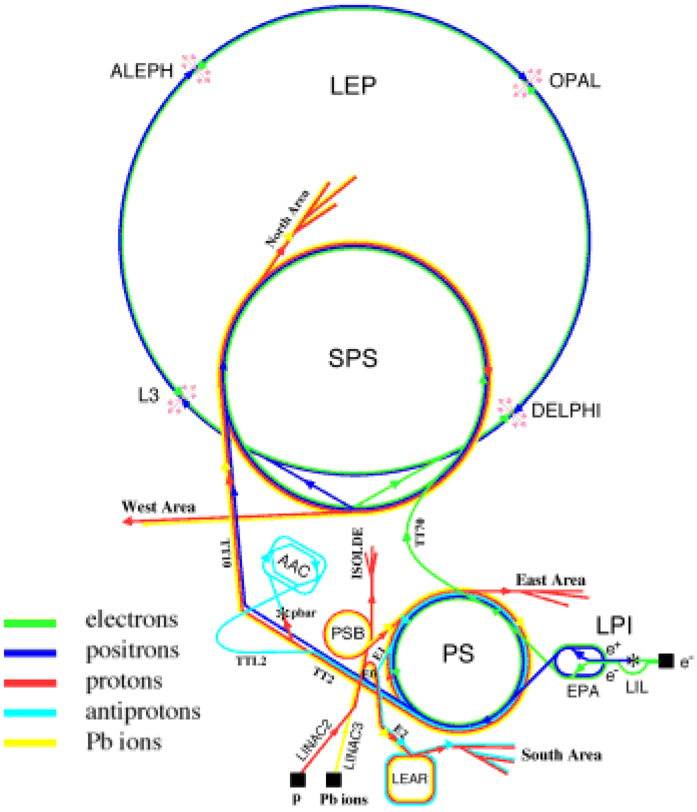
Large Electron Positron (LEP) collider

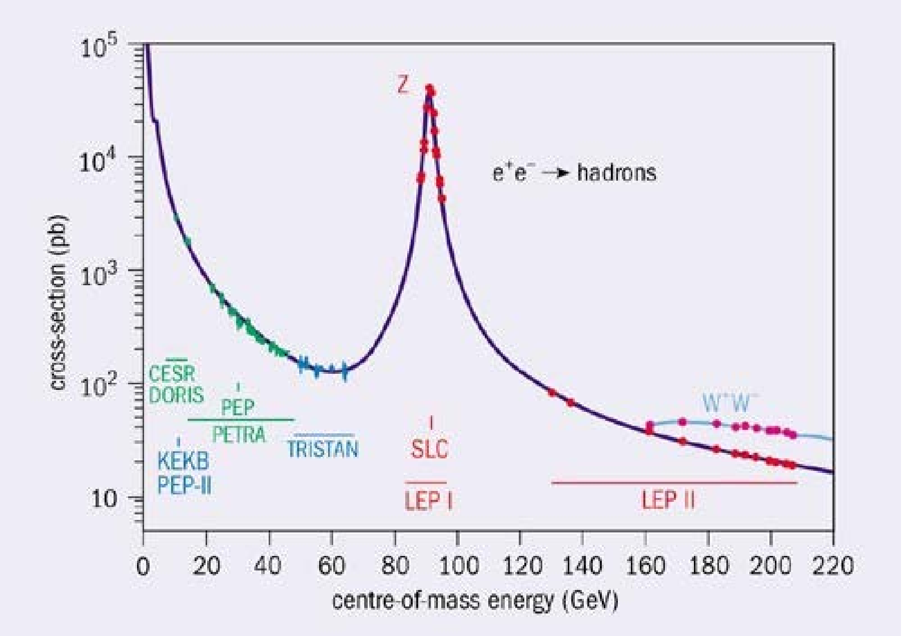
Carlos Rubbia

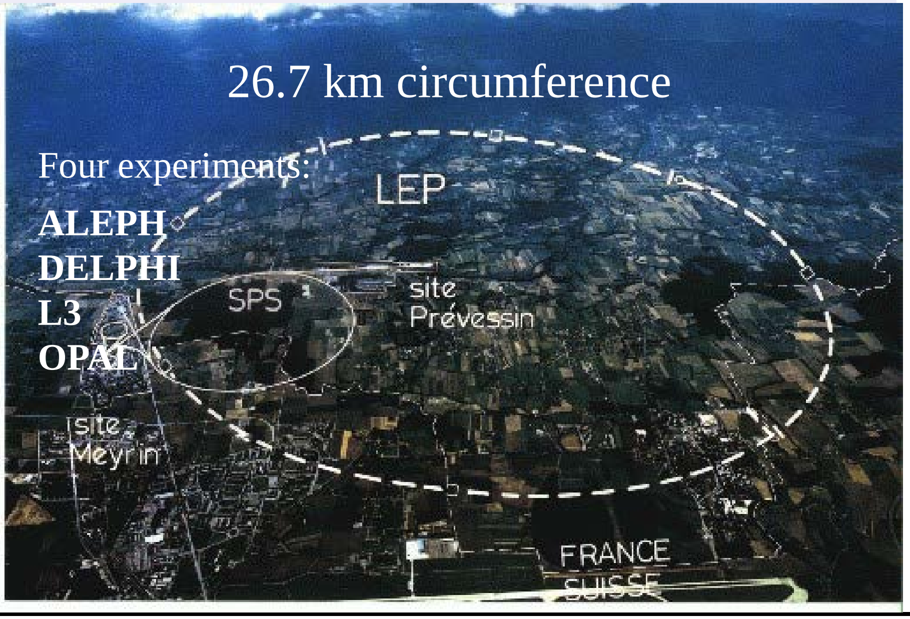
Simon van der Meer

Large Electron-Positron Collider at CERN

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







Large Hadron Collider at CERN

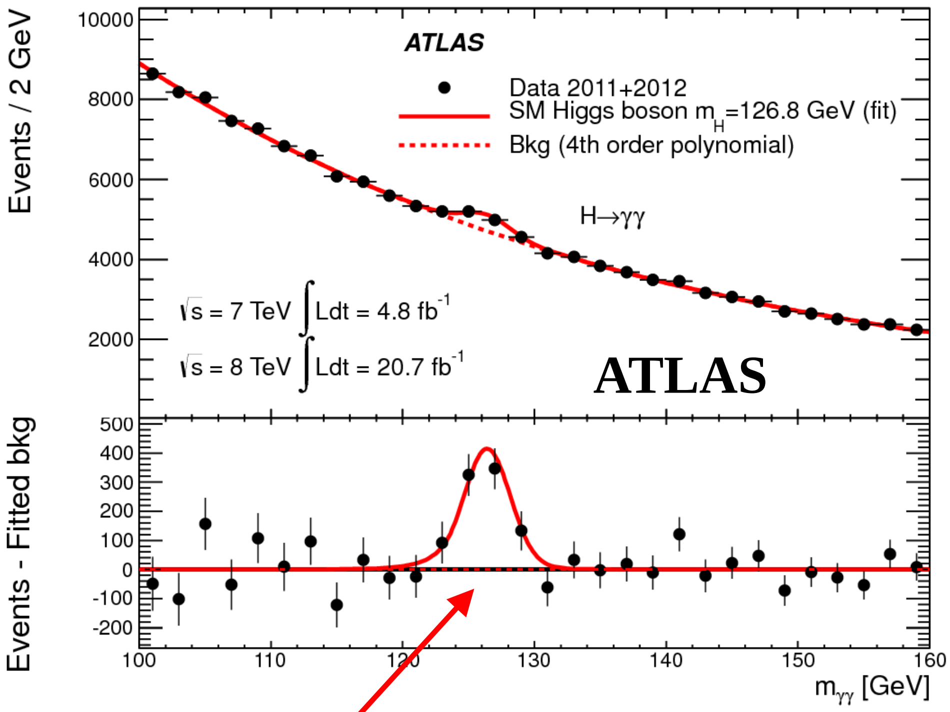
LHC ($p \rightarrow \leftarrow p$)

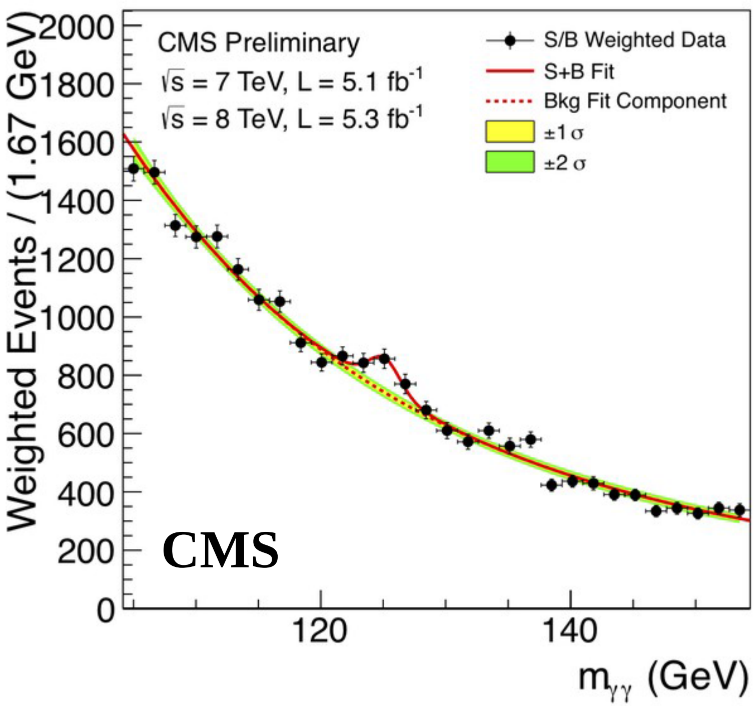
$s^{1/2} \leq 14$ TeV

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