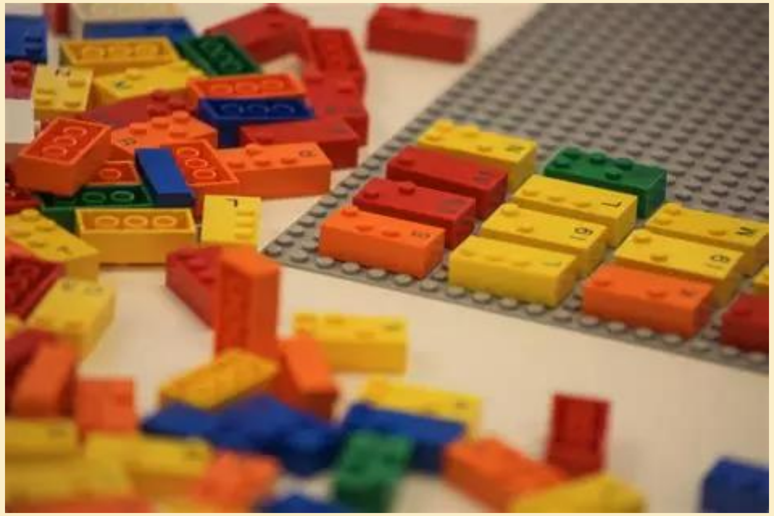
The Standard Model of Particle Physics

In less than two hours… there will be shortcuts!

N. Besson – ISAPP school – 29/03/2022

The building of Standard Model

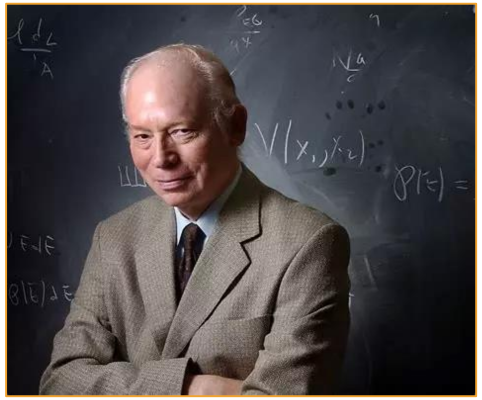


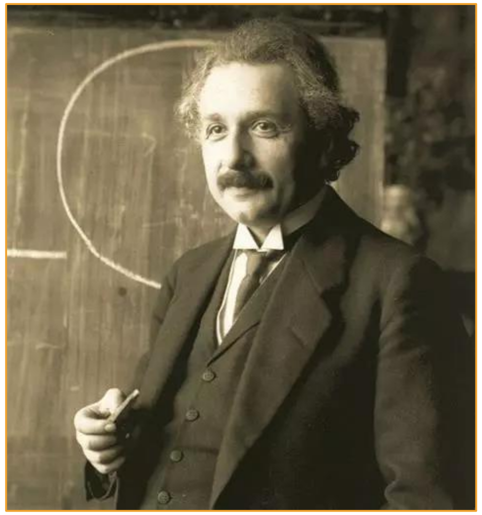
The name of the game

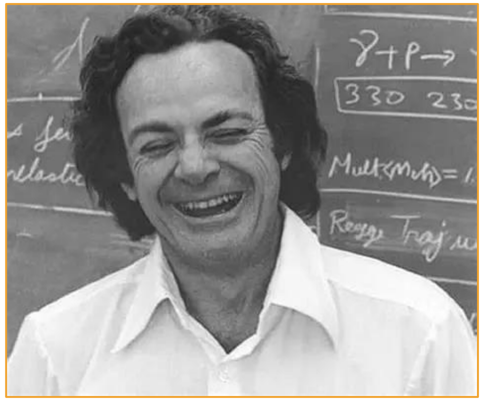
Our job is to see things simply, to understand a great many complicated phenomena in a unified way, in terms of a few simple principles. S. Weinberg

Everything should me made as simple as possible but not simpler. A. Einstein

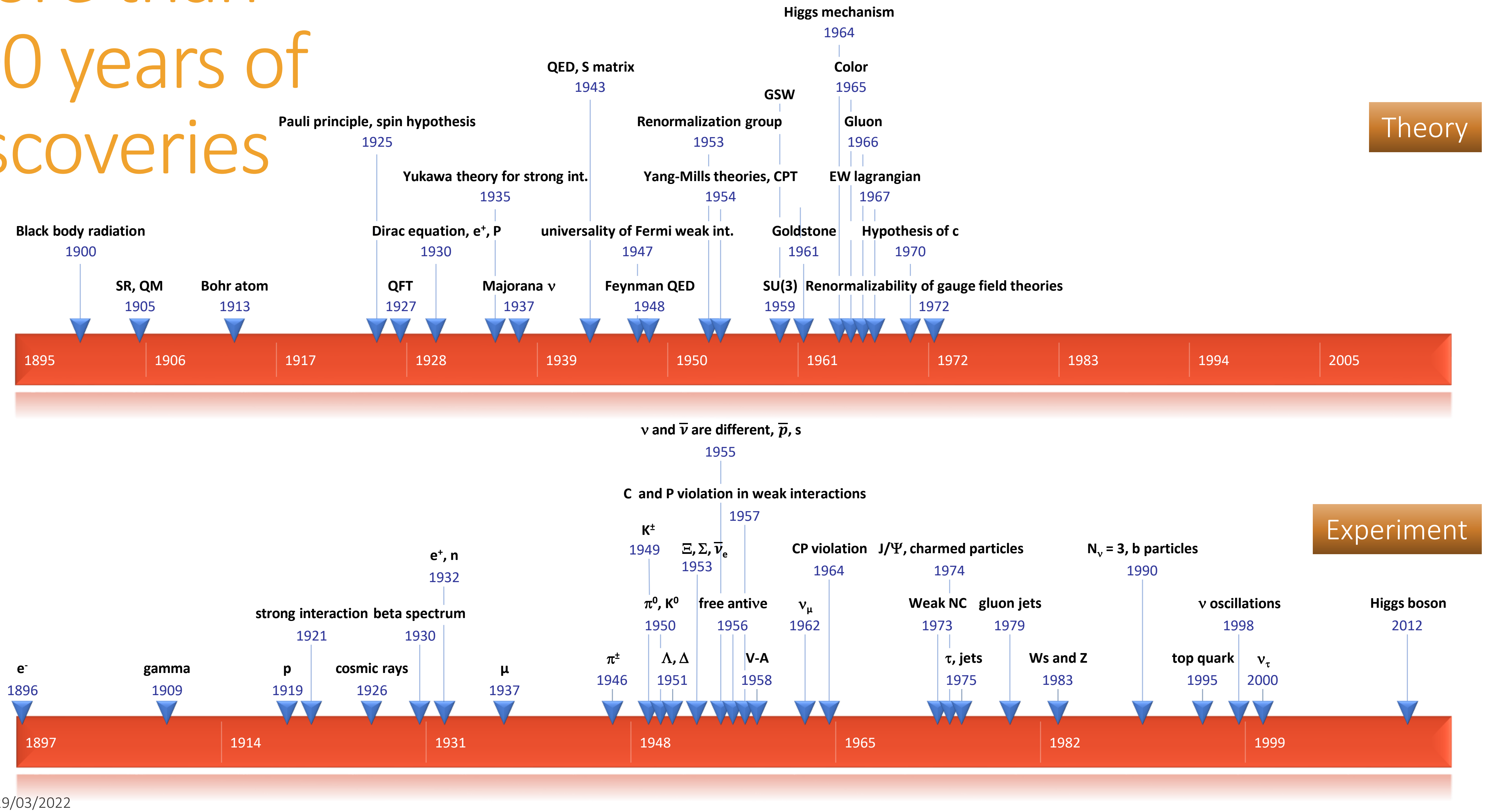
It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong. R. Feynman

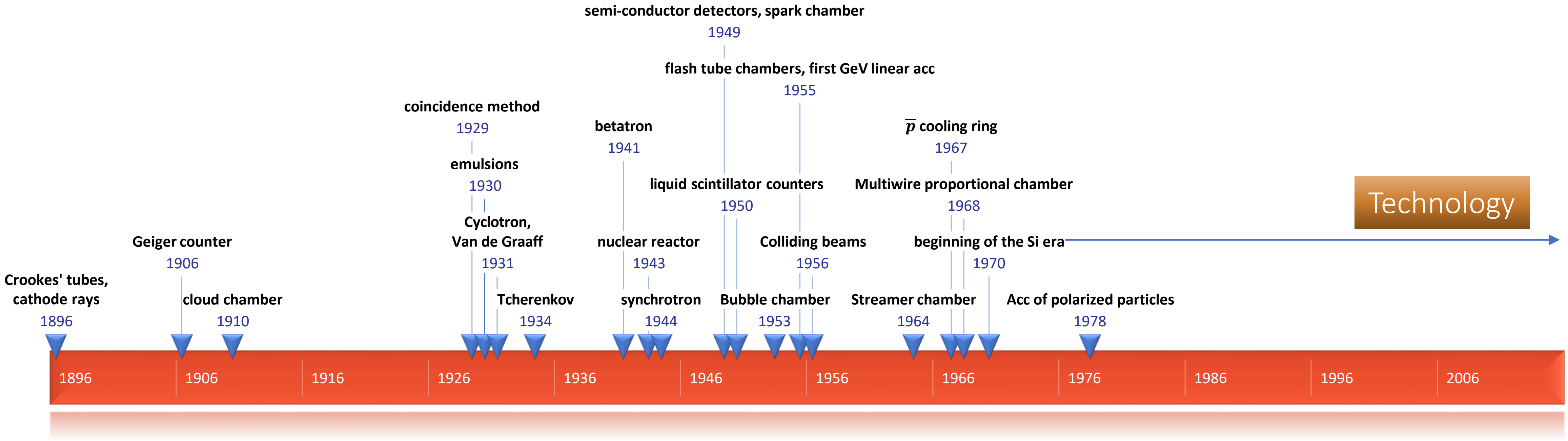






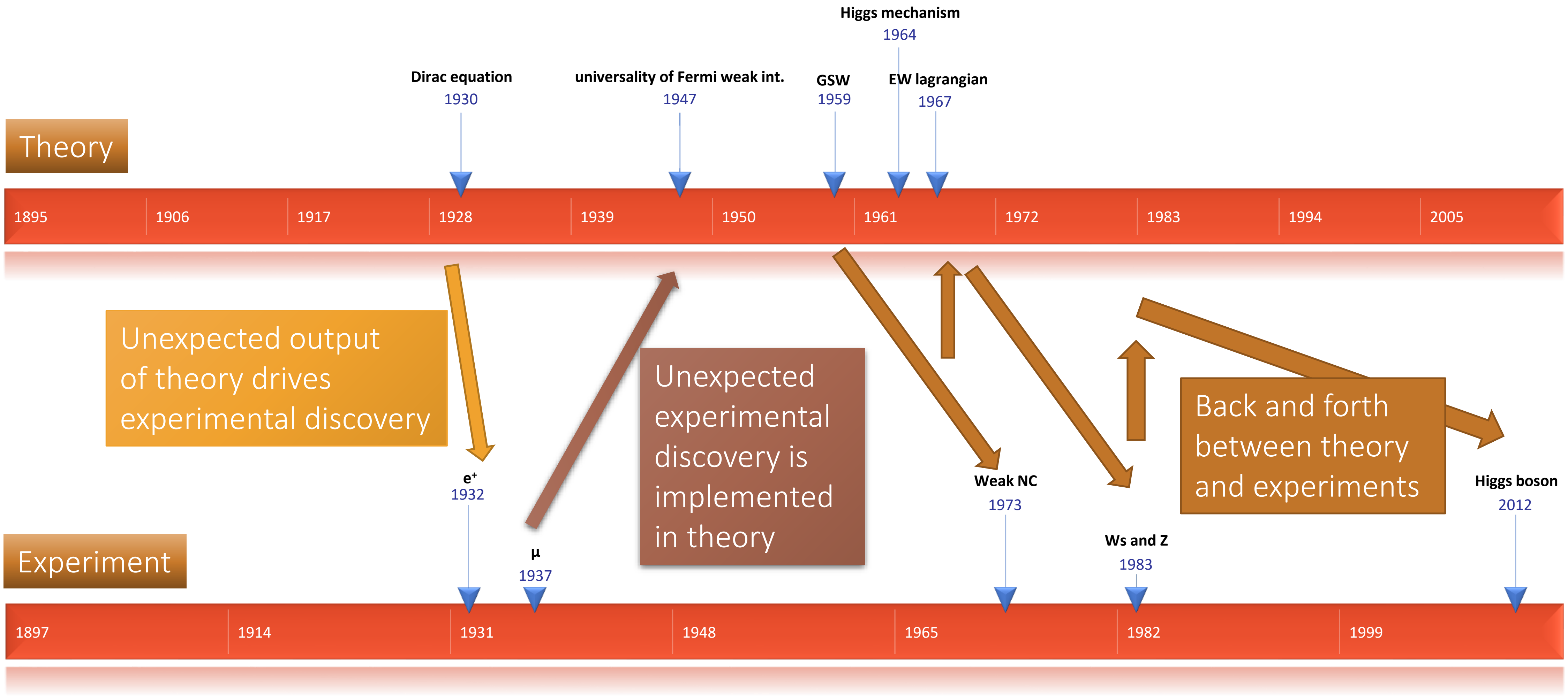
More than 100 years of discoveries

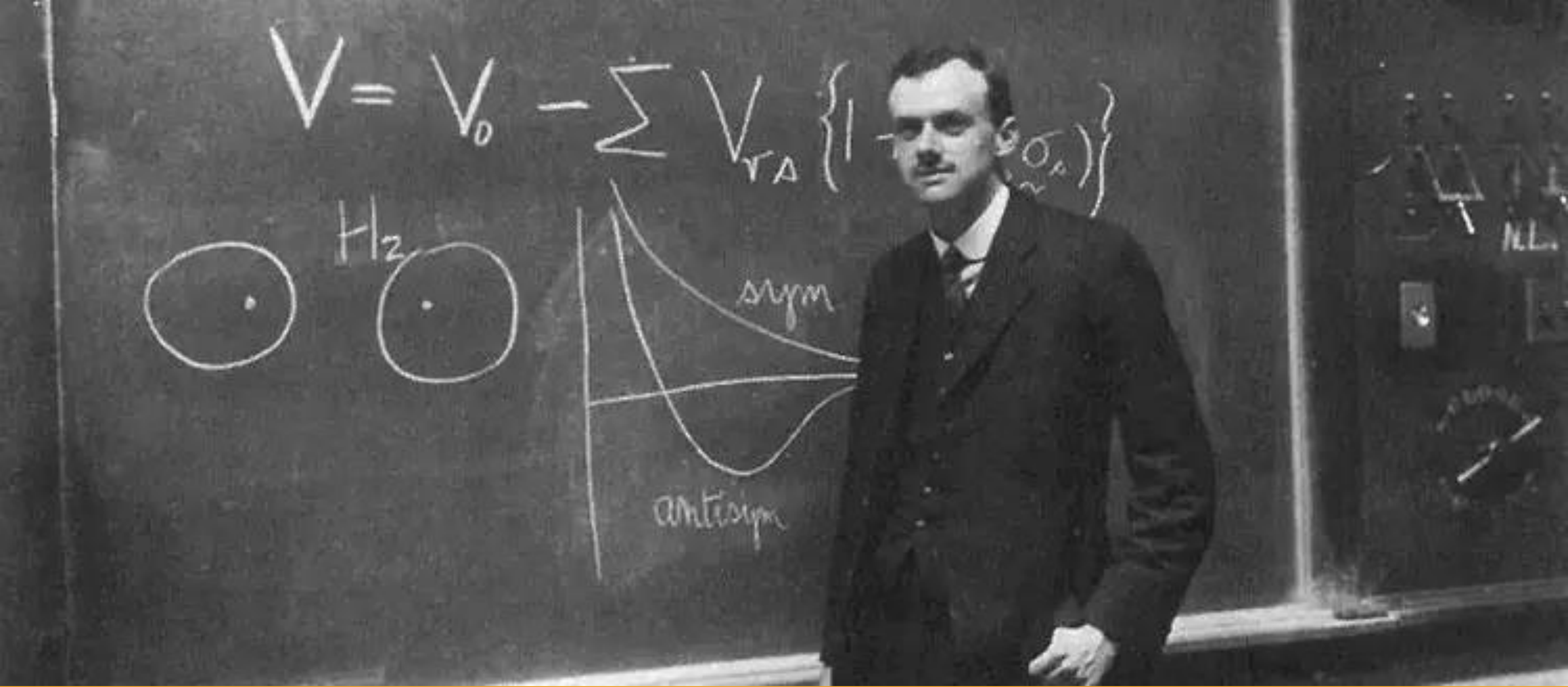




Progress in our knowledge of the content and dynamics
of the Universe at the fundamental level requires
intertwined theoretical, experimental and technological breakthroughs

Three examples





“My equation was smarter than I was”

My equation was smarter than I was

When unexpected output of theory drives experimental discovery

Context:

Quantum Field Theory = union of $\boldsymbol{\hbar}$ (Galilean quantum formalism) and $\boldsymbol{c}$ (classical relativistic formalism)⇒ new length scale: $\lambda_C = \frac{\hbar}{mc}$, new domain of physics of

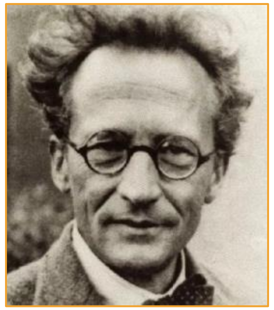
- high energies for which creation and annihilation of particles have to be possible
- $E=mc^2$ gives the transformation rate between matter and energy
- quantum mechanics deals with the probabilities governing the transformation.

Why fields? Varying number of particles for a system in evolution, and Heinsenberg's uncertainty principle forbids to localise objects too precisely so:

- Lagrangian description (energy instead of applied forces)
- Four time-space coordinate. Usual quantum formalism, $\vec{X}$ = operator while $\boldsymbol{t}$ = parameter, not Lorentz-covariant. If operator T, the Hamiltonian has no fundamental state ⇒ $\vec{X}$ = parameter, and operators = functions of x^μ ⇒ operator fields.

⇒ Lagrangian densities $\mathcal{L}\left(\phi(\boldsymbol{x}), \partial_\mu \phi(\boldsymbol{x})\right)$

Dirac's equation



Non-relativistic quantum case, equation for a free particle: quantification of classical expression

$E = \frac{p^2}{2m}$ with: $E \rightarrow i\hbar\partial_t$ and $p \rightarrow -i\hbar\partial_i \Rightarrow -\frac{\hbar^2}{2m}\nabla^2\psi = i\hbar\frac{\partial\psi}{\partial t}$.

Relativistic case, first try: $E^2 - p^2c^2 = m^2c^4 \Leftrightarrow p^\mu p_\mu - m^2c^2 = 0 \Rightarrow -\frac{1}{c^2}\frac{\partial^2\psi}{\partial t^2} + \nabla^2\psi = \left(\frac{mc}{\hbar}\right)^2\psi \Rightarrow$

$\mathcal{L}_{KG} = \frac{1}{2}\partial_\mu\partial^\mu\varphi - \frac{1}{2}m^2\varphi^2$, rehabilitated as the perfectly correct lagrangian for a free spin 0 particle.

Order 2 with respect to time derivation

Relativistic case, second try: linearize by factorizing $p^\mu p_\mu - m^2c^2 = (\beta^\kappa p_\kappa + mc)(\gamma^\lambda p_\lambda - mc)$.

8 unknown parameters and constraints: no linear term in p_κ (Lorentz invariance) i.e. $\beta^\kappa = \gamma^\kappa$

$\Rightarrow (\gamma^0)^2 = 1, (\gamma^i)^2 = -1, \gamma^\lambda\gamma^\kappa + \gamma^\kappa\gamma^\lambda = 0$ for $\lambda \neq \kappa$.

Brilliant solution: $\gamma_0 = \begin{pmatrix} \mathbb{I} & 0 \\ 0 & -\mathbb{I} \end{pmatrix}$ $\gamma_i = \begin{pmatrix} 0 & \sigma_i \\ -\sigma_i & 0 \end{pmatrix}$

$$(i\gamma^\mu\partial_\mu - m)\psi = 0 \text{ avec } \psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix} = \begin{pmatrix} \psi_A \\ \psi_B \end{pmatrix}$$

Solutions to Dirac's equation

Plane wave solution at rest, then Lorentz boost to any momentum:

$$u^1 = \sqrt{(E+m)}\begin{pmatrix} 1 \\ 0 \\ \frac{p_z}{E+m} \\ \frac{(p_x+ip_y)}{E+m} \end{pmatrix} u^2 = \sqrt{(E+m)}\begin{pmatrix} 0 \\ 1 \\ \frac{(p_x-ip_y)}{E+m} \\ \frac{-p_z}{E+m} \end{pmatrix} v^1 = \sqrt{(-E+m)}\begin{pmatrix} \frac{(p_x-ip_y)}{E-m} \\ \frac{-p_z}{E-m} \\ 0 \\ 1 \end{pmatrix} v^2 = \sqrt{(-E+m)}\begin{pmatrix} \frac{p_z}{E-m} \\ \frac{(p_x+ip_y)}{E-m} \\ 1 \\ 0 \end{pmatrix}$$

« At first [Dirac] thought that the spin, or the intrisic angular momentum that the equation demanded, was the key, and that the spin was the fundamental consequence of relativistic quantum mechanics. However, the puzzle of negative energies that the equation presented, when it was solved, eventually showed that the crucial idea necessary to wed quantum mechanics and relativity together was the existence of antiparticles. »

« If we define P as the partity operator which changes the sign of the three spatial directions, T as the time reversal operation which changes the direction of the flow of time, and finally C as charge conjugation which changes particles to antiparticles and vice versa, then operating on a state with P and T is the same as operating on the state with C, that is PT=C »

« In other words this operation PT which changes the sign of everything is really a relativistic transformation, or rather a Lorentz transformation, extended across the spacelike region by demanding that the energy is greater than 0. »

R. Feynman, The 1986 Dirac memorial lectures.

Antiparticles!

The four canonical solutions are:

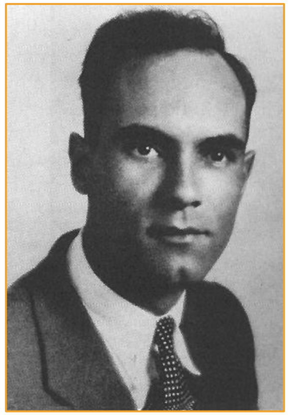
$$u^1 = \sqrt{(E+mc^2)/c}\begin{pmatrix} 1 \\ 0 \\ \frac{cp_z}{E+mc^2} \\ \frac{c(p_x+ip_y)}{E+mc^2} \end{pmatrix}, u^2 = \sqrt{(E+mc^2)/c}\begin{pmatrix} 0 \\ 1 \\ \frac{c(p_x-ip_y)}{E+mc^2} \\ \frac{-cp_z}{E+mc^2} \end{pmatrix}$$

$$v^1 = \sqrt{(E+mc^2)/c}\begin{pmatrix} \frac{c(p_x-ip_y)}{E+mc^2} \\ \frac{-cp_z}{E+mc^2} \\ 0 \\ 1 \end{pmatrix}, v^2 = -\sqrt{(E+mc^2)/c}\begin{pmatrix} \frac{cp_z}{E+mc^2} \\ \frac{c(p_x+ip_y)}{E+mc^2} \\ 1 \\ 0 \end{pmatrix}$$

A particle can then be described by $\psi(x) = ae^{-ip.x}u(x)$ and an anti-particle by $\psi(x) = ae^{+ip.x}v(x)$.

Dirac's lagrangian is then $\mathcal{L}_D = \bar{\psi}(i\gamma^\mu\partial_\mu - m)\psi$ (with ($\bar{\psi} = \psi^\dagger\gamma^0$)

Discovery of the positron



In 1931, Dirac postulates antimatter.

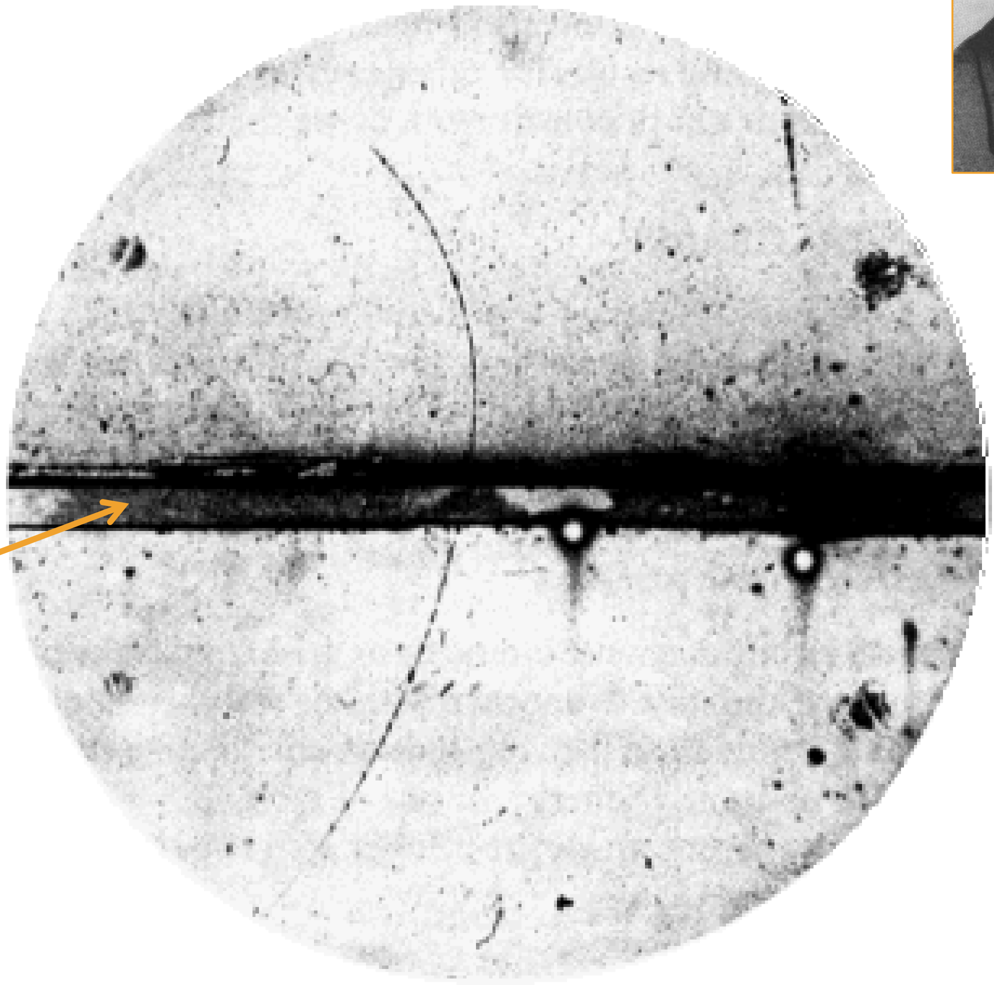
In 1932, Carl Anderson discovers it!

Source: cosmic rays (Hess 1912)

Detector: cloud chamber (Wilson 1912)

Magnetic field + energy loss in the material ⇒ electrical charge

Lead plate to rule out the hypothesis of an electron travelling in the opposite direction



Anderson, Physical Review 43, 491 (1933)

Out of 1300 photographs, fifteen have positive tracks!

$$q < 2\, q_e \text{ and } m < 20\, m_e$$

Antimatter timeline

1931, Dirac, antimatter, *Quantised singularities in the electromagnetic field*,133Proc. R. Soc. Lond. A

1932, Anderson, observation of positron, *The Positive Electron*, Physical Review 43, 491

1932, Blackett and Occhialini, electron-positron pair creation, *Photography of Penetrating Corpuscular Radiation.* Nature 130, 363 (1932)

1934, Joliot-Curie, β+ decay (and artificial radioactivity), Comptes rendus hebdomadaires des séances de l'Académie des sciences, 15 janvier 1934

1955, Chamberlain & Segrè, antiproton, *Observation of Antiprotons,* Phys. Rev. 100, 947

1956, Cork et al., antineutron, *Antineutrons Produced from Antiprotons in Charge-Exchange Collisions,* Phys. Rev. 104, 1193

1995, Oelert et al., anti-hydrogen, *Production of anti-hydrogen,* Phys.Lett. B368 (1996) 251-258

Let's go a little bit further

Gauge theories e.g. Electromagnetism

Maxwell equations: $\vec{\nabla}.\vec{E} = \rho$ (i) $\vec{\nabla}.\vec{B} = 0$ (ii) $\vec{\nabla} \wedge \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}$ (iii) $\vec{\nabla} \wedge \vec{B} = \frac{1}{c}\frac{\partial \vec{E}}{\partial t} + \frac{1}{c}\vec{j}$ (iv)

Minkowski's formalism, anti-symmetrical rank 2 tensor $F^{\mu\nu} = \begin{pmatrix} 0 & -E_x & -E_y & -E_z \\ E_x & 0 & -B_z & B_y \\ E_y & B_z & 0 & -B_x \\ E_z & -B_y & B_x & 0 \end{pmatrix}$ and a 4-vector $J^\mu(c\rho, \vec{j})$

Equations (ii) and (iii) $\Rightarrow \vec{B} = \vec{\nabla} \wedge \vec{A}$ and $\vec{E} = -\vec{\nabla}\phi - \frac{1}{c}\frac{\partial \vec{A}}{\partial t}$, with ϕ scalar potential and $\vec{A}$ vector potential.

Minkowski's formalism: $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$ with $A^\mu\left(\phi, \vec{A}\right)$

In terms of potentials, $\partial_\mu \partial^\mu A^\nu - \partial^\nu\left(\partial_\mu A^\mu\right) = \frac{1}{c} J^\nu$

Potentials determined up to a global gradient: $A'_\mu = A_\mu + \partial_\mu f(x^\mu)$ follows also $F^{\mu\nu} = \partial^\mu A'^\nu - \partial^\nu A'^\mu$.

These changes of potentials which do not affect the fields are gauge transformations ($\phi \rightarrow \phi + \frac{1}{c}\frac{\partial f}{\partial t}, \vec{A} \rightarrow \vec{A} - \vec{\nabla} f$ where f is any function of the space-time coordinates).

Local invariance

$\mathcal{L} = \bar{\Psi}(i\gamma^\mu \partial_\mu - m)\Psi$ invariant under global gauge transformation (U(1)) $\Psi(x) \rightarrow e^{-i\alpha}\Psi(x)$ with α a global phase

Locality (independence of distant points in space) ⇒ invariance by local phase change $\Psi(x) \rightarrow e^{-iq\alpha(x)}\Psi(x)$

Derivative part of the lagrangian transforms like $\partial_\mu \Psi(x) \rightarrow e^{-iq\alpha(x)}[-iq\partial_\mu \alpha(x) + \partial_\mu]\Psi(x) \Rightarrow$

the lagrangian of a free particle is not locally invariant.

To preserve local invariance, new gauge vector field, covariant derivative $D_\mu \Psi = \partial_\mu \Psi + iqA_\mu \Psi$ with $A^\mu \rightarrow A^\mu + \partial^\mu \alpha$.

$\mathcal{L} = \bar{\Psi}(i\gamma^\mu D_\mu - m)\Psi$ invariant under local transformation.

Complete lagrangian: "free" term for the vector field $\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{{m_A}^2}{2}A^\mu A_\mu$ with $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ (field tensor)

$F_{\mu\nu}F^{\mu\nu}$ invariant by $A^\mu \rightarrow A^\mu + \partial^\mu \alpha$, but $\frac{{m_A}^2}{2}A^\mu A_\mu \rightarrow \frac{m_A^2}{2}(A^\mu + \partial^\mu \alpha)(A_\mu + \partial_\mu \alpha) \neq \frac{{m_A}^2}{2}A^\mu A_\mu \Rightarrow$ massless field

This is electromagnetism!

A step further toward QED

$$\mathcal{L} = \bar{\Psi}(i\gamma^\mu D_\mu - m)\Psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$\Leftrightarrow$$

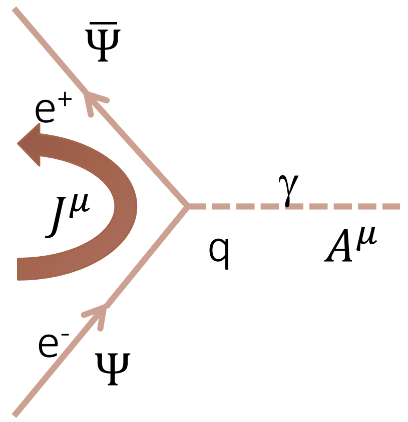
$$\mathcal{L} = \underbrace{\bar{\Psi}(i\gamma^\mu \partial_\mu - m)\Psi}_{\text{Free fermion}} - \underbrace{\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{Free photon}} - \underbrace{\mathrm{q}\bar{\Psi}\gamma_\mu\Psi A^\mu}$$

Free fermion

Free photon

Coupling of a Noether current $J_\mu = \mathrm{q}\bar{\Psi}\gamma_\mu\Psi$ with gauge field A^μ and amplitude q

QED elementary vertex



What did we learn?

And what I did forget to mention…

Quantum dynamics requires a description based on a lagrangian density, function of the fields and their first derivatives. Ask that it is

1. Invariant under symmetries:
   Lorentz-covariant, and local invariance for gauge symmetries
2. At most quadratic in the fields (i.e. renormalizable)
3. Dealing with positive energies

You get: particles and their antiparticles, describded by quantum numbers, in interaction with massless gauge fields

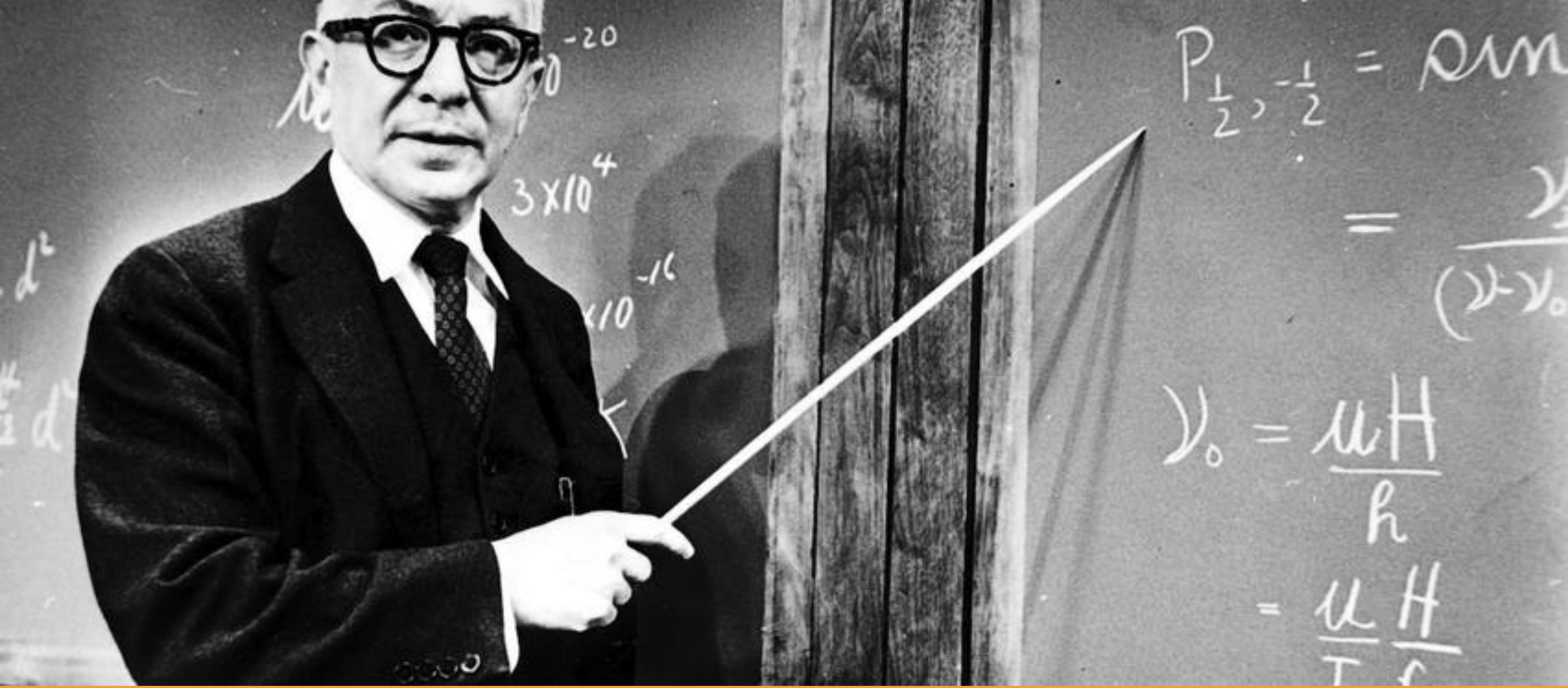
space-time symmetry $\Rightarrow$ spin, mass

Internal gauge symmetries like U(1)$\Rightarrow$ electric charge

And conservation laws (Noether's theorem, « *a monument of mathematical thought* » A. Einstein).

1954: recipe by Yang&Mills to build quantum dynamics

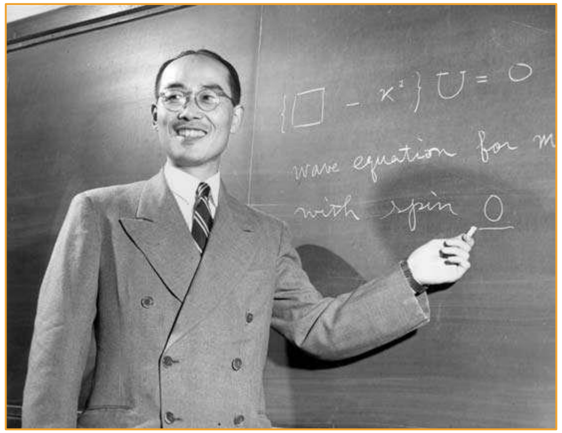
Summary: QED is a theory which is Abelian (commutative), gauged (invariance under continuous local phase change), renormalisable (valid to all orders). It describes interactions and propagation of a current (the electron), and of a gauge boson (the photon), which are coupled via the electric charge. The boson is massless which preserves gauge invariance and describes the infinite range of electromagnetic interactions.



``Who ordered that?”

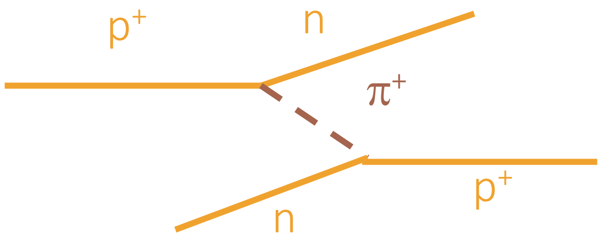
Who ordered that?

Unexpected discovery to implement in the model



Context:
Rutherford: size of nuclei incompatible with Coulomb repulsion
Heisenberg: n and p bound by permanent electron exchange but this kind of exchange does not conserve spin.
1935, Yukawa: postulate of bosons exchanged between p and n in nuclei.

$$p \rightarrow n\,\pi^{+}$$
$$n \rightarrow p\,\pi^{-}$$
$$p \rightarrow p\,\pi^{0}$$
$$n \rightarrow n\,\pi^{0}$$



Three spin 0 bosons in three states of charge
boson mass related to the range of the interaction, size of nuclei ~ 10^{-15} m $\Rightarrow$ m ~ 200 MeV/c².

New cosmic rays

1936, observation of a new type of rays in a cloud chamber with curvature intermediate between those of the electrons and other types of particles like p, in two charge states ⇒

Mass greater than m_e but smaller than m_p, hence their (temporary) name "mesotron".

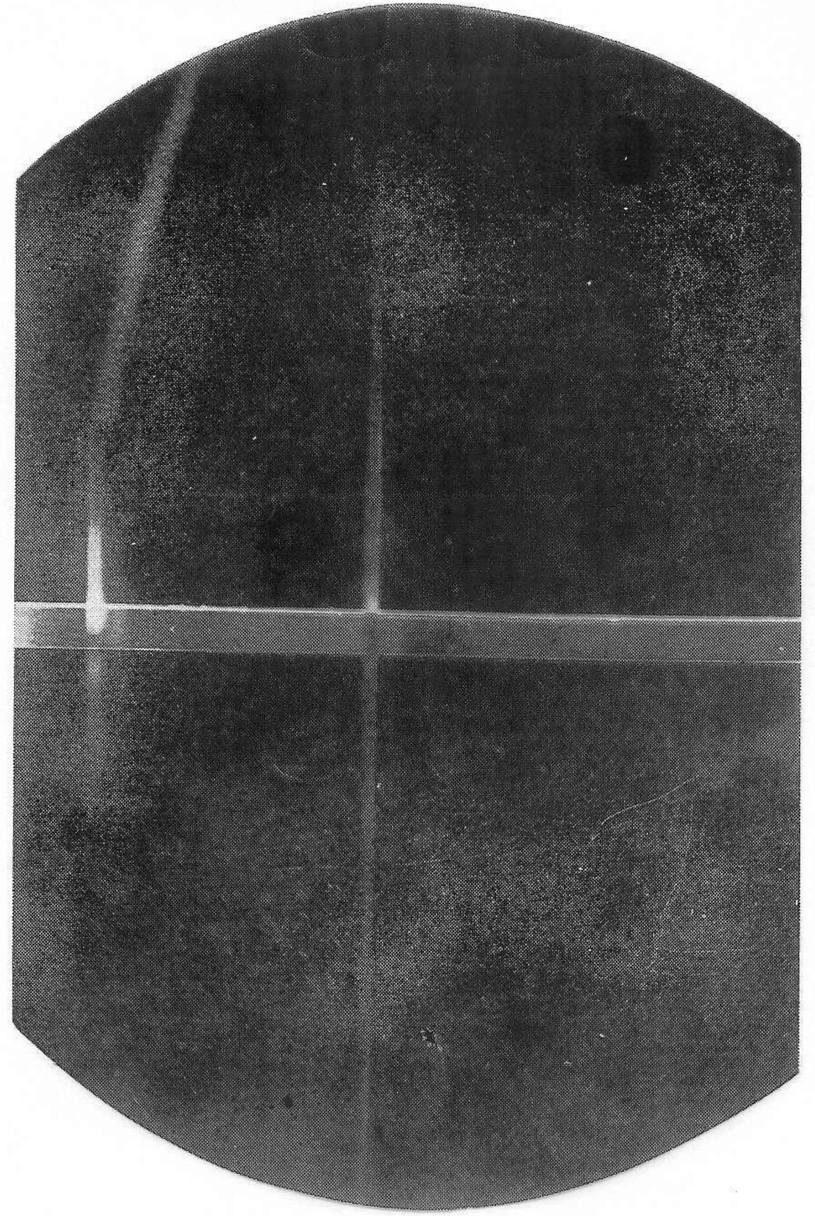
$$m_e < m < m_p$$

C. D. Anderson and S. H. Neddermeyer, *Cloud Chamber Observations of Cosmic Rays at 4300 Meters Elevation and Near Sea-Level*

S. H. Neddermeyer and C. D. Anderson, *Note on the Nature of Cosmic-Ray Particles*

Confirmation in 1937:

J. C. Street and E. C. Stevenson, *New Evidence for the Existence of a Particle of Mass Intermediate Between the Proton and Electron*



Cloud-chamber picture of a meson. From Street and Stevenson

Mesotrons

These new particles decay, their lifetime is measured by comparing fluxes at different altitudes with cloud chambers

B. Rossi, N. Hilberry, and J. Barton Hoag, *The Variation of the Hard Component of Cosmic Rays with Height and the Disintegration of Mesotrons*

$\tau = 2{,}15 \pm 0{,}07\ \mu s$

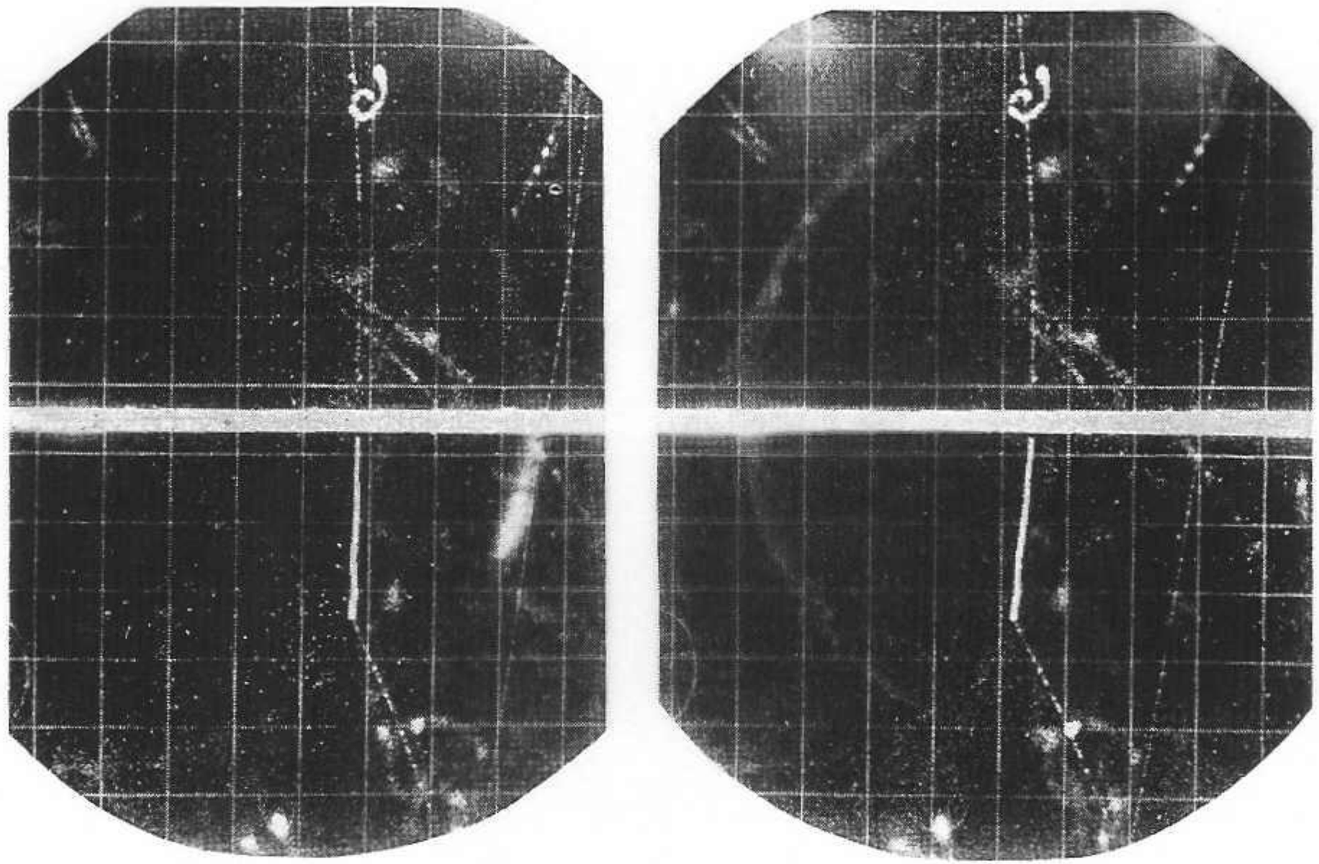


Fig. 4.7.2. Stereoscopic photographs of a meson stopping in the gas of a cloud chamber and disintegrating with the emission of an electron. From R. W. Thompson

Leptons

1947, new detector developped by C.Powell: photographic emulsions, which allow to see and time mesotrons decays and prove that there are two types of mesotrons:

- One sensitive to strong interaction (not a surprise)
- One LEPTON (opposed to hadrons) relatively light particle not subject to strong interaction, just like the electron. Totally unexpected

« Who ordered that? » famously exclaimed I. Rabi

Muon vs pion

pion

Strong interaction

$\pi \rightarrow \mu \ (+ \nu)$

τ = 2,6 10^{-8} s

m = 139 MeV

muon

Not sensitive to strong interaction (no nuclear capture)

$\mu \rightarrow e \ (+ 2\nu)$

τ = 2,2 10^{-6} s

m = 106 MeV

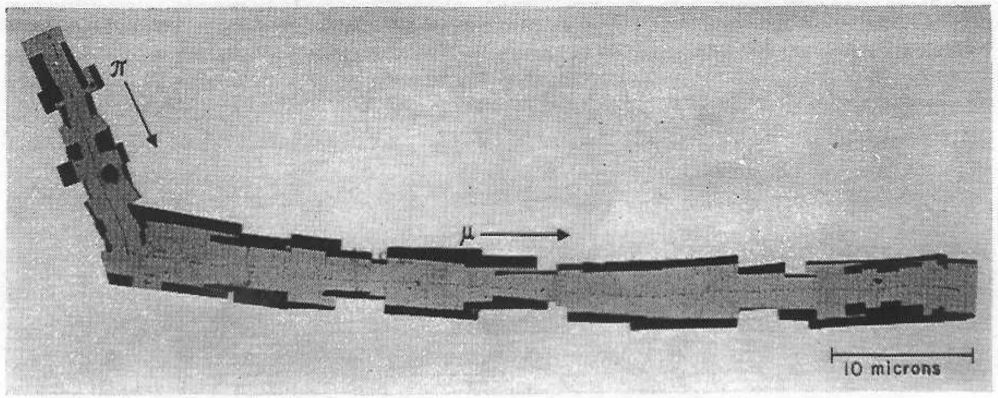


Fig. 4.8.1. Mosaic of microphotographs showing a $\pi \rightarrow \mu$ decay in Ilford C2 emulsion. From Lattes *et al.* (LCM47.1).

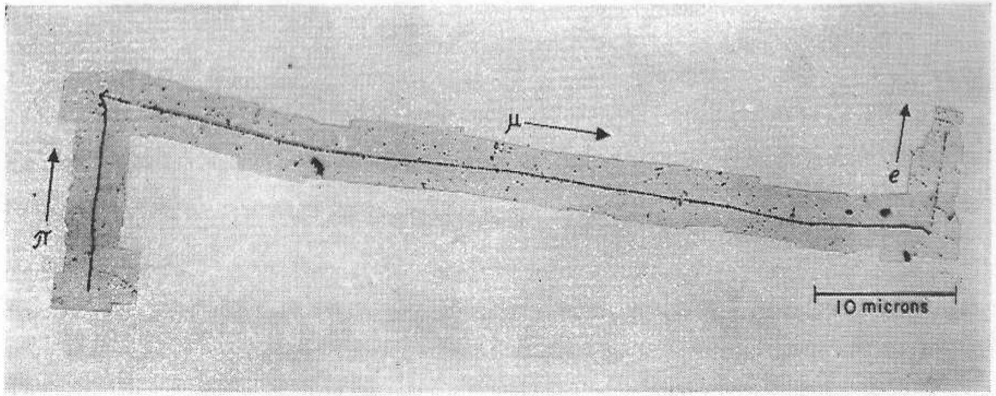
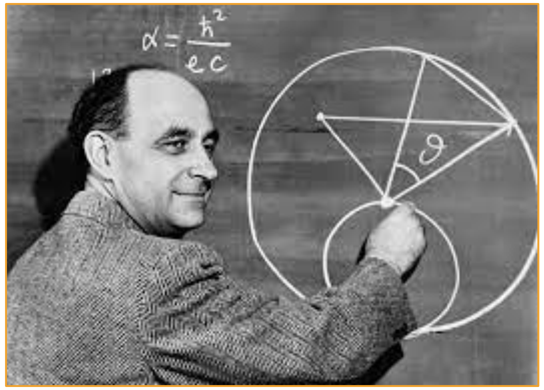


Fig. 4.8.2. Mosaic of microphotographs showing a $\pi \rightarrow \mu \rightarrow e$ decay. Kodak NT4 electron-sensitive emulsion. From Brown *et al.* (BRH49.2).

Let’s go a little bit further

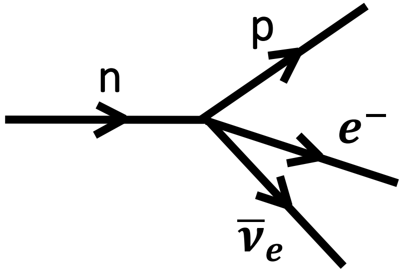


Weak interaction:

Historical elements :

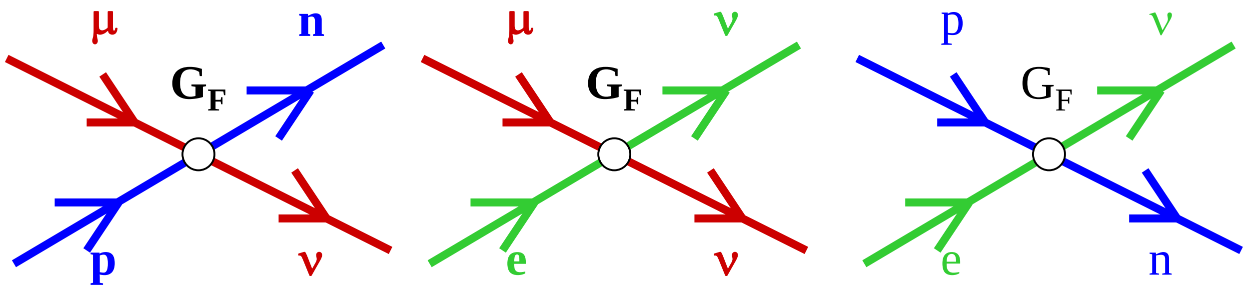
1930 Pauli postulates the existence of the neutrino

1934 Fermi proposes a theory for β decays, by analogy with QED $\mathcal{L}_F = -\frac{G_F}{\sqrt{2}} J^{\mu}_{hadr}(x) J^{lept}_{\mu}(x)$, contact interaction characterized by a coupling constant $G_F = 10^{-5}$ GeV^{-2}



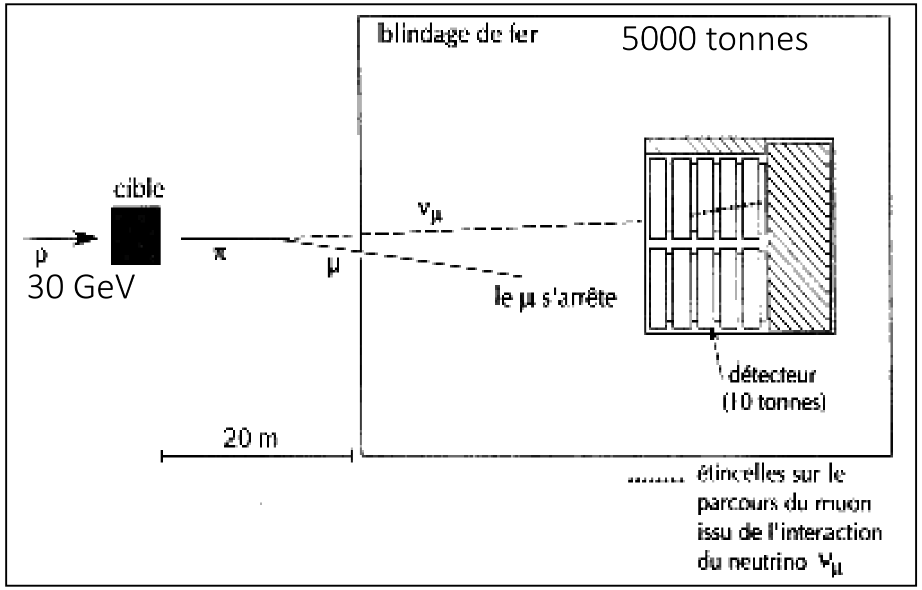
1947 universality of weak interactions, one unique constant to take into account:

- β^- decay $n \rightarrow p^+ + e^- + \bar{\nu}_e$
- β^+ decay $p^+ \rightarrow n + e^+ + \nu_e$
- Electron capture $e^- + p^+ \rightarrow n + \nu_e$
- Muon decay $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$
- Muon capture $\mu^- + p^+ \rightarrow n + \nu_\mu$



Muon neutrino

G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz, and J. Steinberger, *Observation of High-Energy Neutrino Reactions and the Existence of Two Kinds of Neutrinos*



$$\pi \rightarrow \mu + \nu$$
$$\nu + N \rightarrow \mu + X$$
$$\nu + N \rightarrow \not{e} + X$$

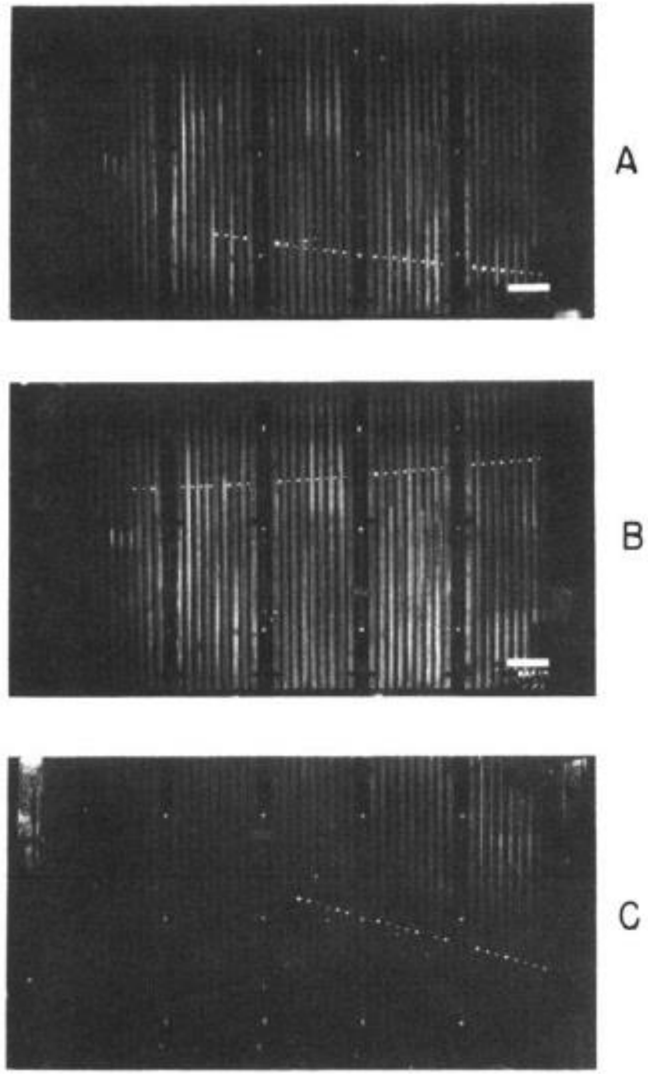


FIG. 5. Single muon events. (A) $p_\mu > 540$ MeV and δ ray indicating direction of motion (neutrino beam incident from left); (B) $p_\mu > 700$ MeV/c; (C) $p_\mu > 440$ with δ ray.

Leptonic numbers

By observing that neutrinos resulting from the disintegration of a pion into a muon can interact on nuclei to give muons and not electrons, physicists determine two new quantum numbers independently conserved: N_e and N_μ

The electron and the electron neutrino are the only ones with a non-zero electron lepton number, their antiparticles have an opposite number. This justifies that during a β decay: $n \rightarrow p^+ + e^- + \bar{\nu}_e$ an electronic antineutrino is emitted (experimentally verified, the particle in question interacts to give a positron and not an electron).

The muon and the muon neutrino share a muonic lepton number (this justifies that neutral pion decays do not give a muon and a positron).

Lepton	Q	N_e	N_μ
Electron e^-	-1	+1	0
Neutrino ν_e	0	+1	0
Muon μ^-	-1	0	+1
Neutrino ν_μ	0	0	+1

What did we learn?

And what very important pieces I did skip…

After EM, the second piece of the standard model are weak interactions.

Particles are arranged in families or generations

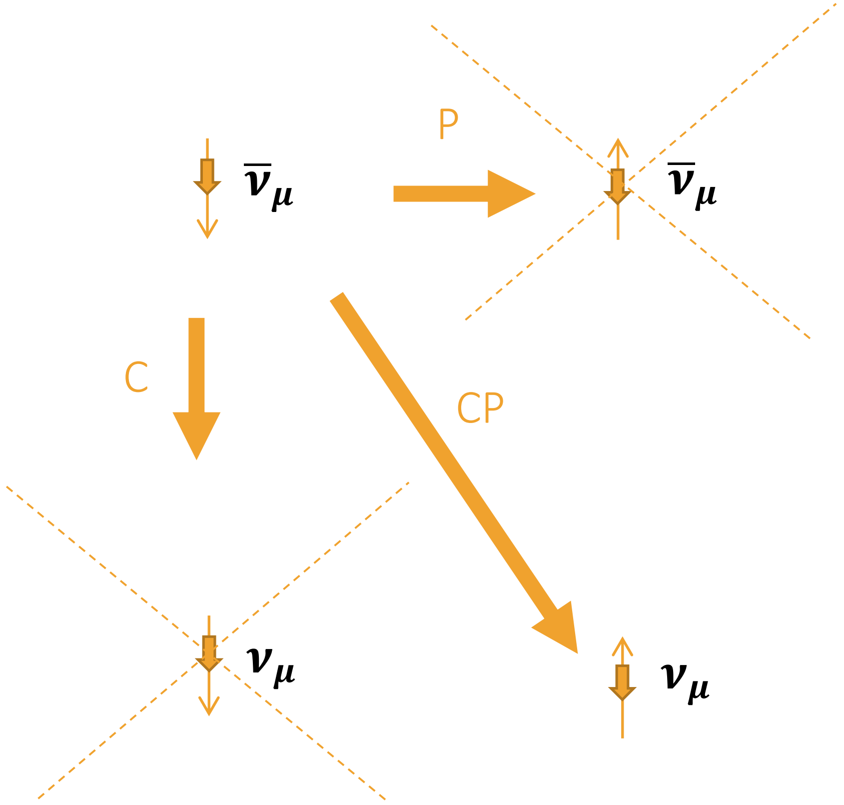
More internal symmetries (U(1) symmetry group): lepton number for ex.

Helicity = projection of spin on the direction of flight. A particle has a right-handed helicity if its spin and momentum are in the same directions, left-handed otherwise. Parity flips the helicity.

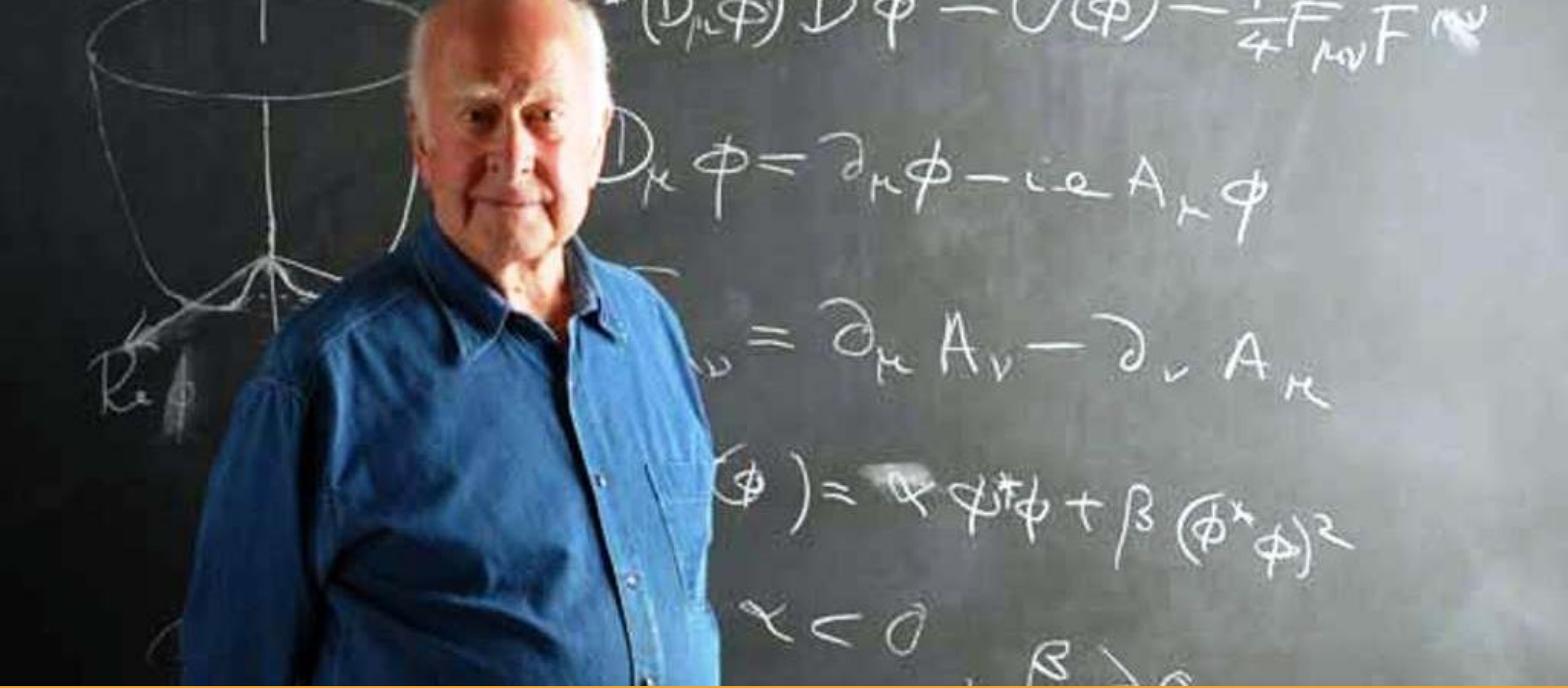
Maximum violation of $\mathcal{P}$ in weak interactions is accompanied by a maximal violation of $\mathcal{C}$.

The weak interaction only concerns the (right)left part of the (anti)particles. It therefore only produces neutrinos of left helicity and anti-neutrinos of right helicity. Since neutrinos are only sensitive to the weak interaction, they only exist a priori in this state!

E.g.: only the right antineutrinos exist. Their image by $\mathcal{P}$, left antineutrinos do not exist but their image by $\mathcal{CP}$ left neutrinos exist.



Wu, C. S.; Ambler, E.; Hayward, R. W.; Hoppes, D. D.; Hudson, R. P. (1957). "Experimental Test of Parity Conservation in Beta Decay". Physical Review. 105 (4): 1413–1415

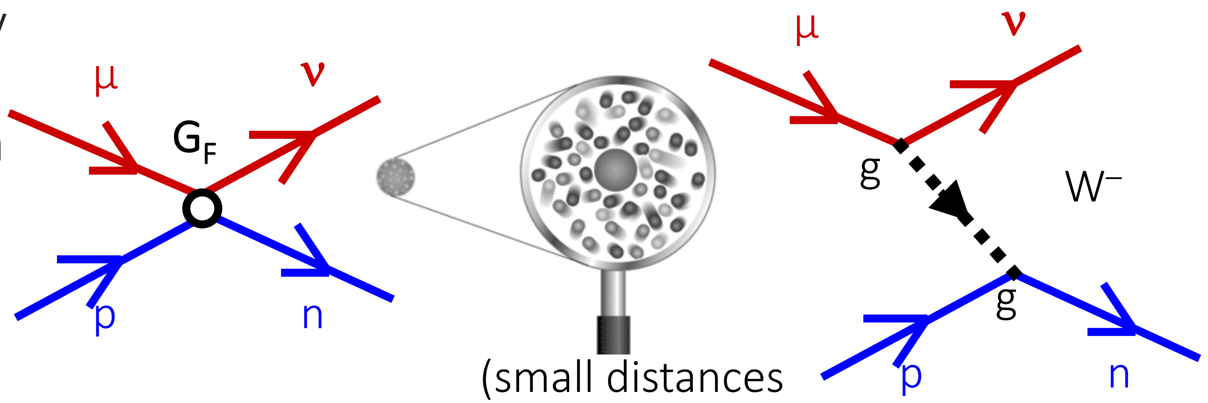


“When you look at a vacuum in a quantum theory of fields, it isn’t exactly nothing.”

When you look at a vacuum in a quantum theory of fields, it isn't exactly nothing.

Context:

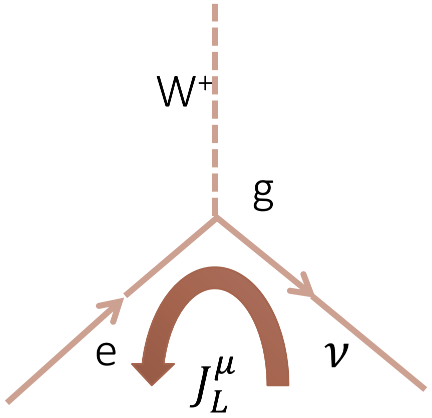
Fermi theory + parity violation = good low-energy predictions. But Dimensioned coupling constant GF~10^{-5} GeV^{-2} $\Rightarrow$ divergent cross sections at high energy (~100 GeV). Non-renormalisable theory!

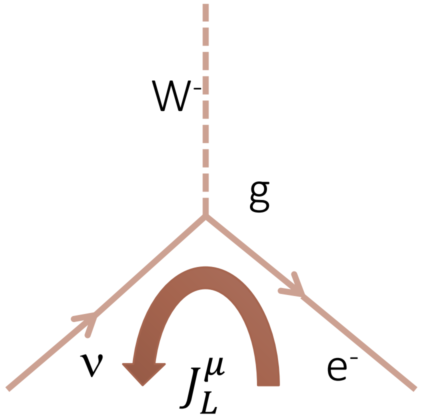


(small distances = high energy)

Solution proposed by Schwinger in 1957: replace contact interaction by the exchange of vector bosons.

Two types of charged currents are observed:

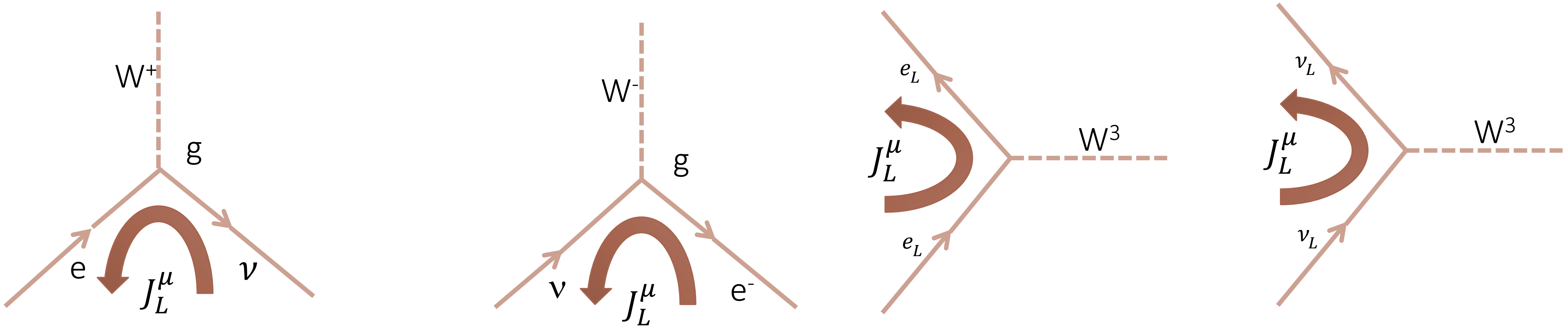




The bosons must be **very massive** to account for the short range of weak interactions. (100 GeV/c²)

Electroweak unification

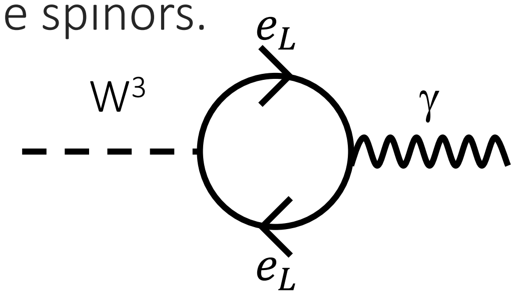
Theoretical constraint: building a weak lagrangian « à la QED » implies a neutral intermediate vector boson in addition to the two charged ones needed to explain beta decays (number of generators of the symmetry group SU(2)):



Can it be the photon? Can electromagnetism be unified with weak interactions in a single symmetry group? No, because :

- The coupling amplitude with W^3 is the weak coupling which is different from the EM coupling...
- The photon coupling is democratic between the left and right parts of the spinors.

However, there is an overlap between electromagnetism and the neutral current part of the weak interactions because of such diagrams



Solution of Glashow, Salam and Weinberg

Introduce a new symmetry U(1) with vector field B and charge Y, choosen so that the mixing between W^3 and B results in A, the photon. Symmetry group: $SU(2)_L xU(1)_Y$

Lagrangian $\mathcal{L} = \bar{\Psi} i\gamma^\mu D_\mu \Psi - \frac{1}{4} F^i_{\mu\nu} F_i^{\mu\nu} - \frac{1}{4} G_{\mu\nu} G^{\mu\nu}$

Imposing local invariance:

$D_\mu = \partial_\mu + igT_i W^i_\mu + ig' \frac{Y}{2} B_\mu$ cov. derivative

g, g' $SU(2)_L xU(1)_Y$ couplings

$F^i_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu - g\varepsilon^i_{jk} W^j_\mu W^k_\nu$ *gauge tensors*

$G_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$

And four Intermediate Boson Vectors(IVB)

W^i_μ, i=1,2,3 et B_μ

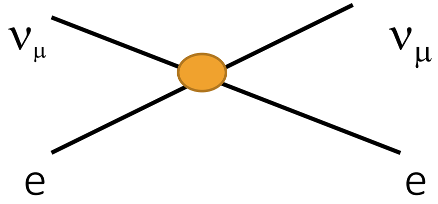
$$W^3 = \cos\theta_W Z_0 + \sin\theta_W A$$
$$B = -\sin\theta_W Z_0 + \cos\theta_W A$$

Double spinor $\begin{pmatrix} \nu_L \\ e_L \\ \nu_R \\ e_R \end{pmatrix}$ charge Q = $\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$

$$\mathcal{L}_{int} = i\bar{f}\gamma^\mu \partial_\mu f - \frac{g}{\sqrt{2}}\left(\bar{\nu}_L \gamma^\mu e_L W^-_\mu + \bar{e}_L \gamma^\mu \nu_L W^+_\mu\right) - \frac{g}{2\cos\theta_W}\left(\bar{f}\gamma^\mu (g_v - g_a\gamma^5) f Z_\mu\right) + e\bar{f}\gamma^\mu Q f A_\mu$$

Hypothesis of neutral vector boson No mass term

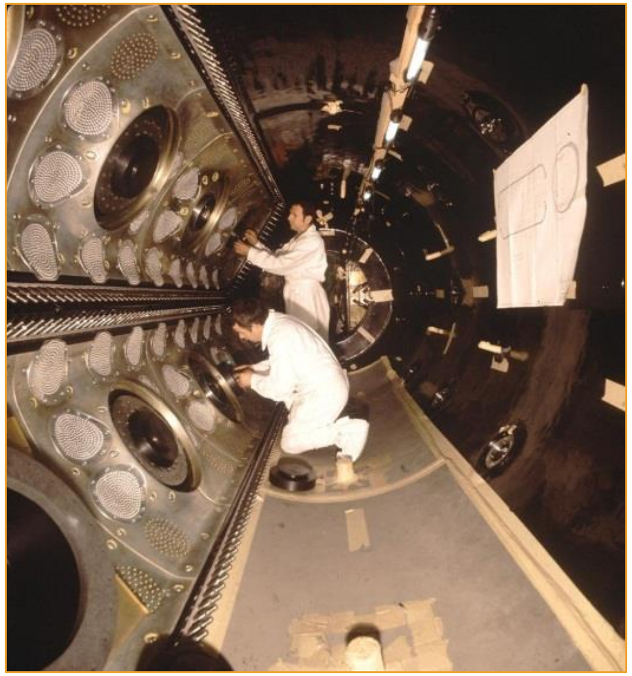
Neutral currents

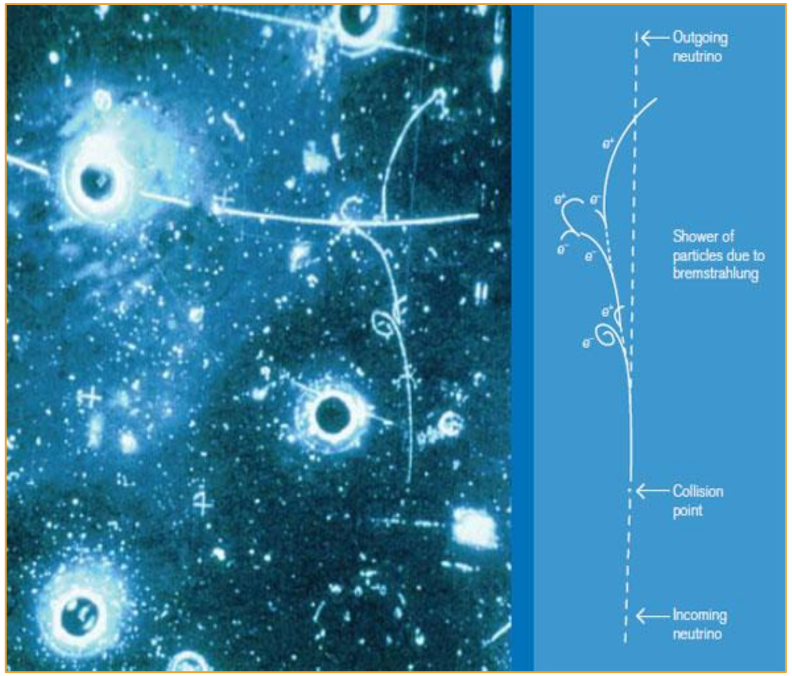


If theory right new neutral boson and prediction of $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$

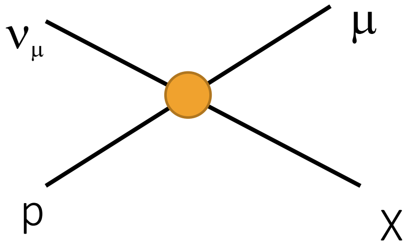
Observed at CERN in 1973 in GARGAMELLE bubble chamber (beam of muon neutrinos and muon antineutrinos on 6.3 m^3 CF3Br).

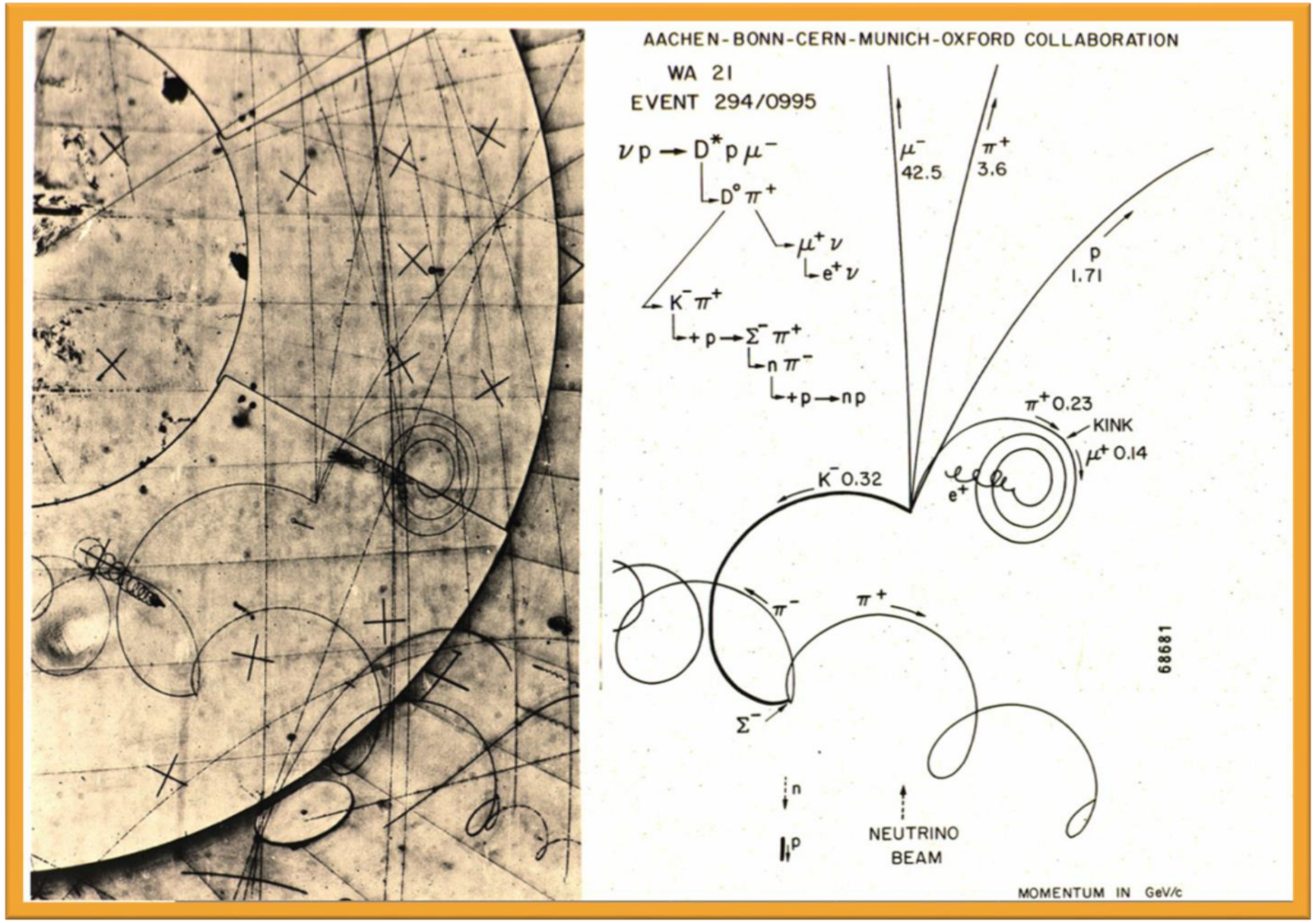
NB: to be sure we test the NCs and not EM: neutrinos and leptonic numbers.





Charged currents





SeArch for Intermediate vector bosons

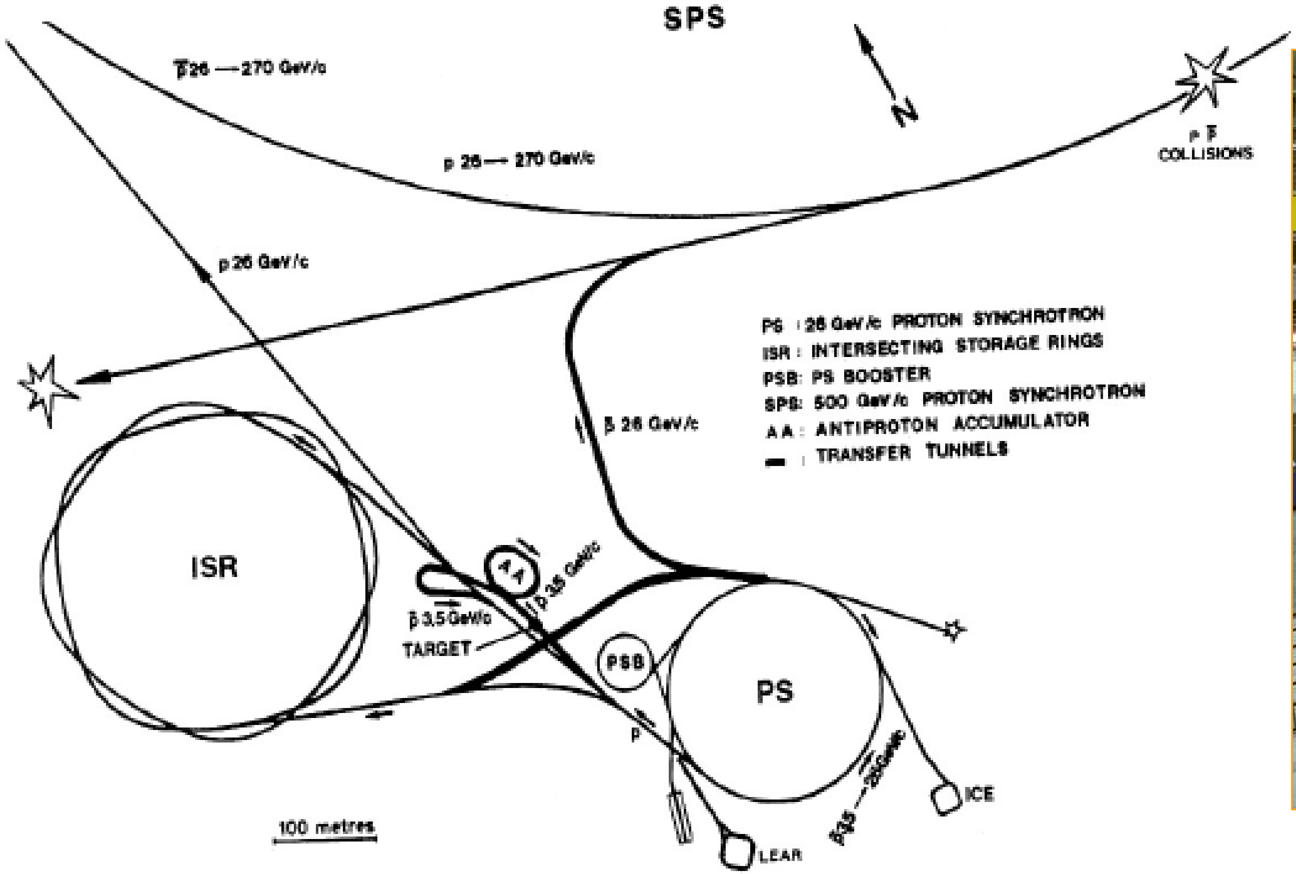
Experiments at Gargamelle → prediction of the Z and W bosons masses, of the order of 60-80 GeV/c^2 for the W and 75-95 GeV/c^2 for the Z. Much too high to allow the use of the "cleanest" modes of production with the available accelerators of the time:

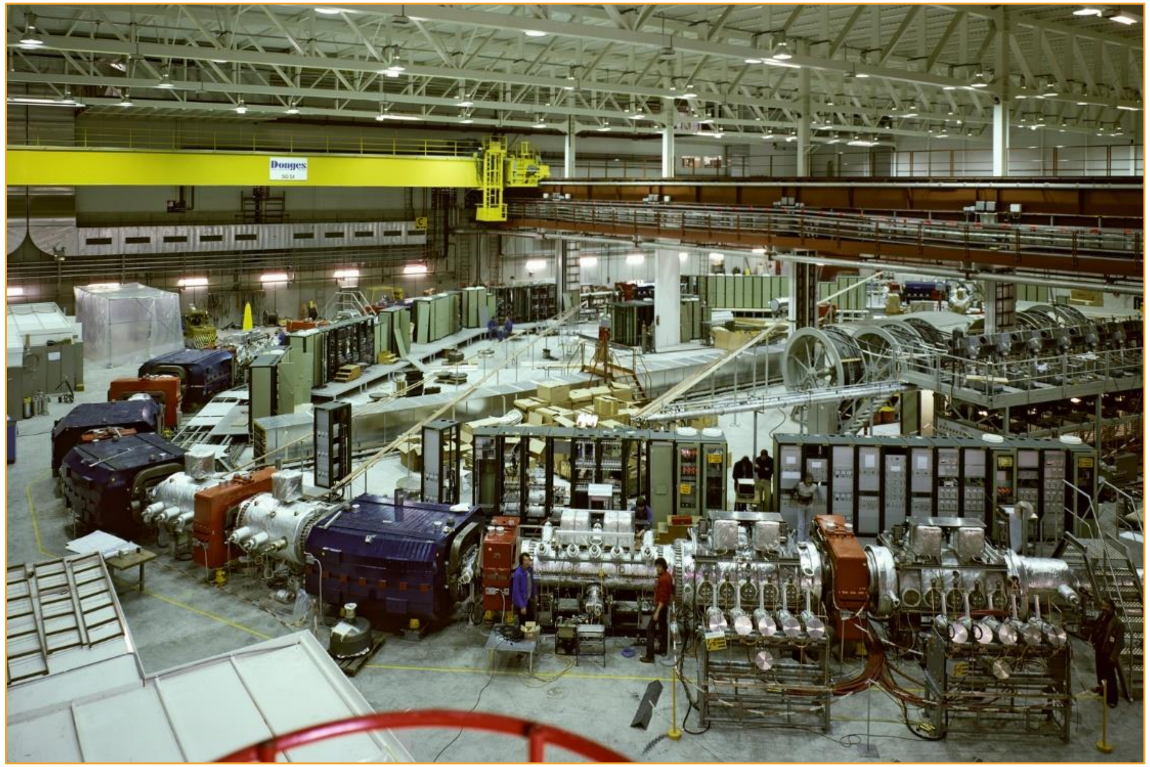
$$e^+e^- \rightarrow Z, e^+e^- \rightarrow W^+W^-$$

The solution is proposed by C. Rubbia and S. Van der Meer: beam of antiprotons, collisions $p\bar{p}$ to have $u\bar{d} \rightarrow W^+, \bar{u}d \rightarrow W^-, u\bar{u}(d\bar{d}) \rightarrow Z$

The proton beam is the 450 GeV beam from the SPS at CERN.

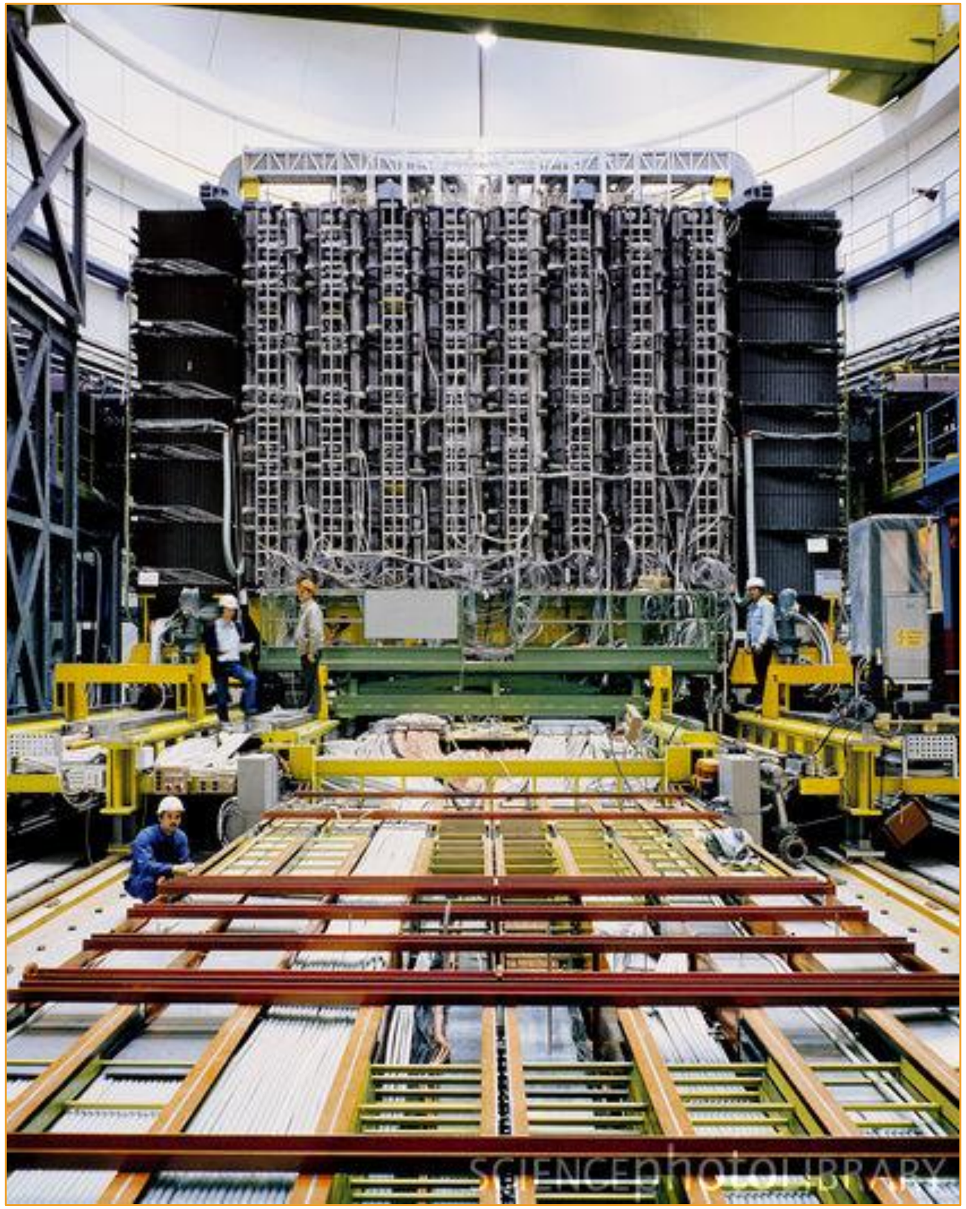
Accelerators at CERN (beginning of 80's)



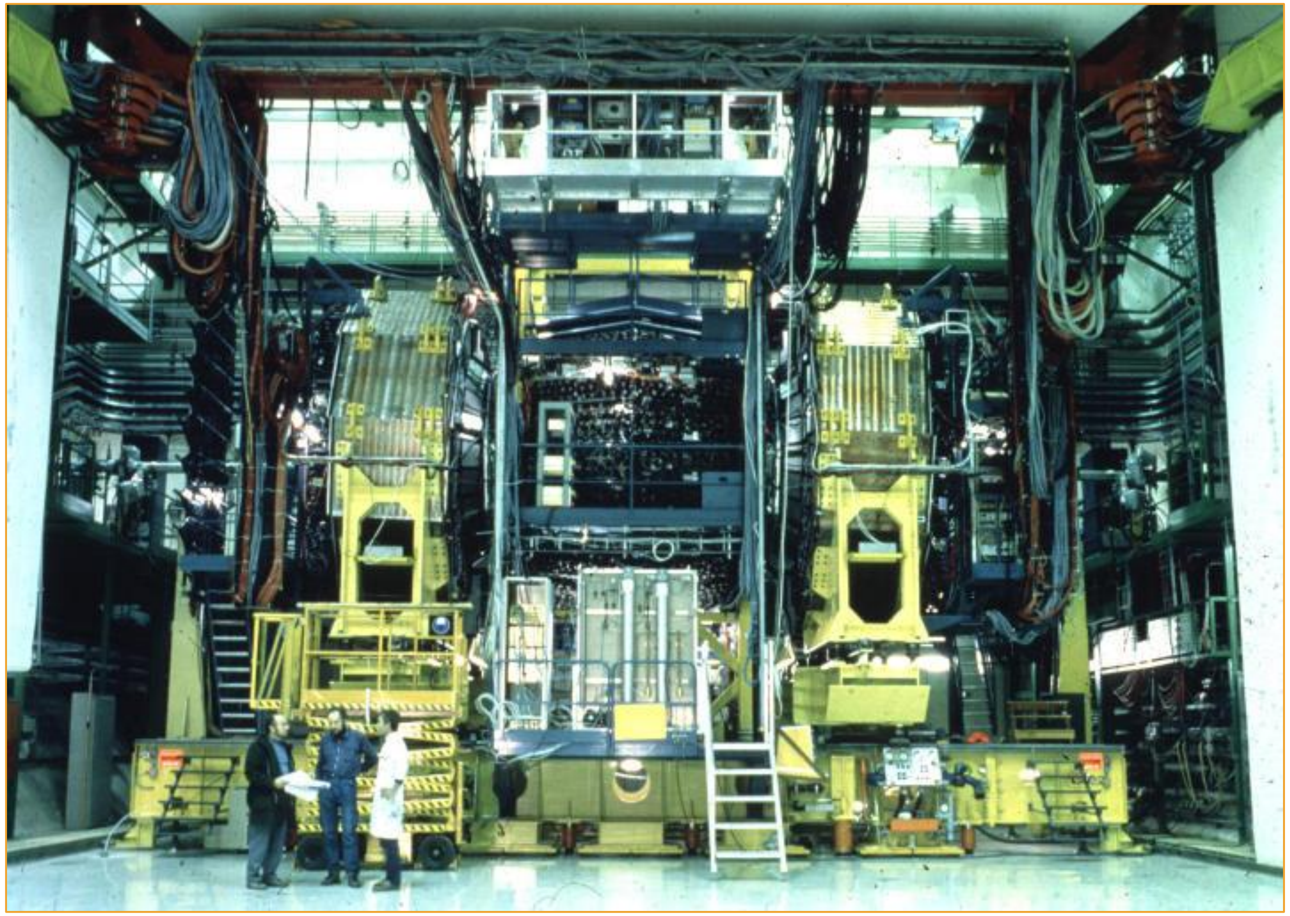


Antiproton Accumulator (AA)

New type of detectors



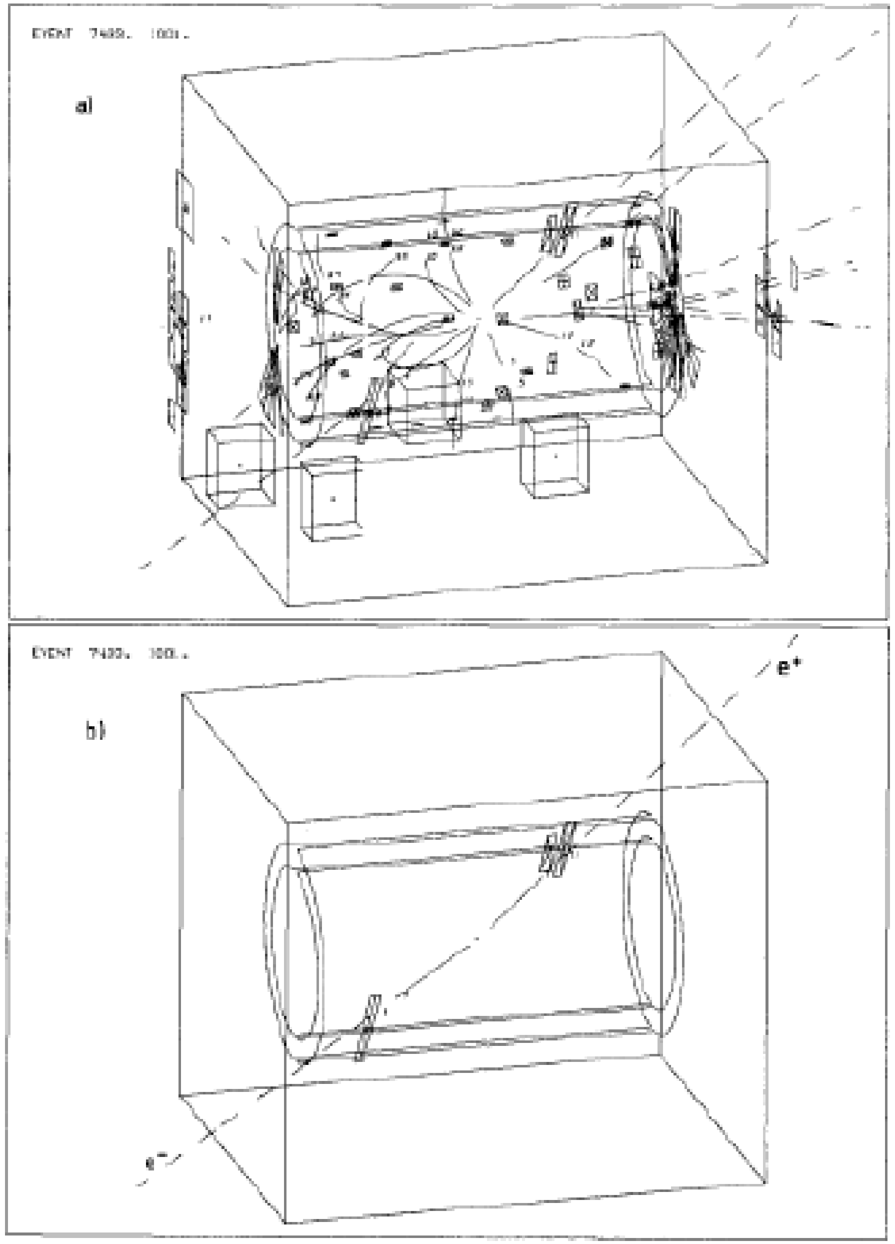
UA1 experiment



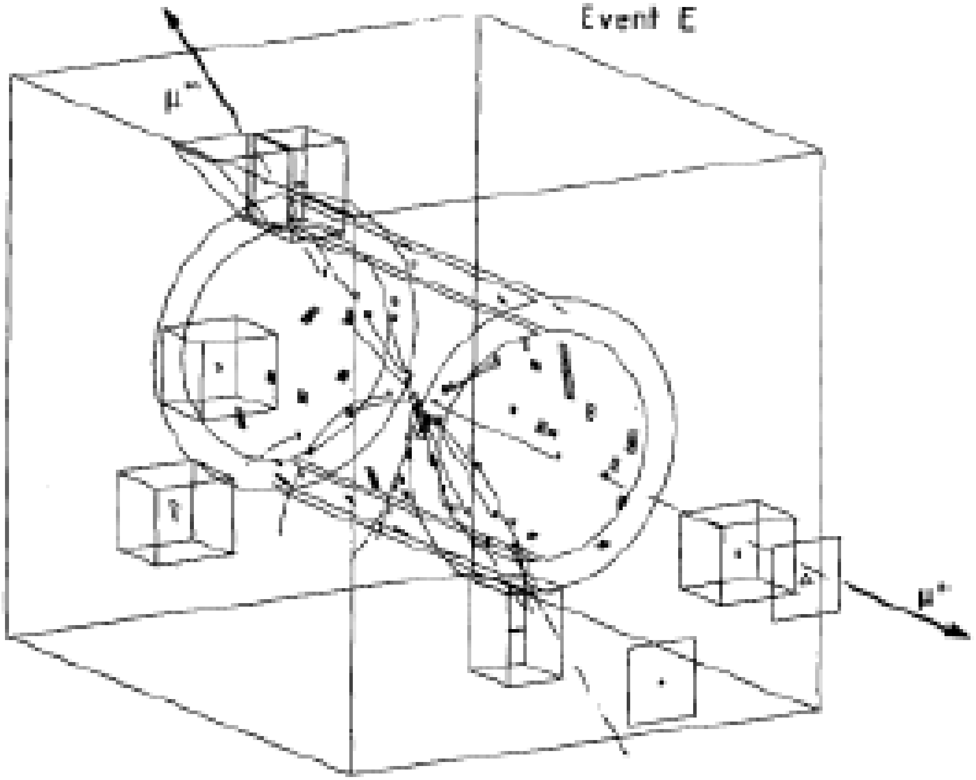
UA2 experiment

$Z \rightarrow e^+e^-$

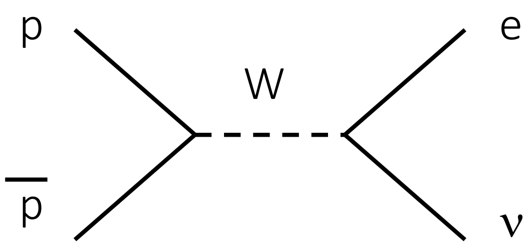
Z events in UA1

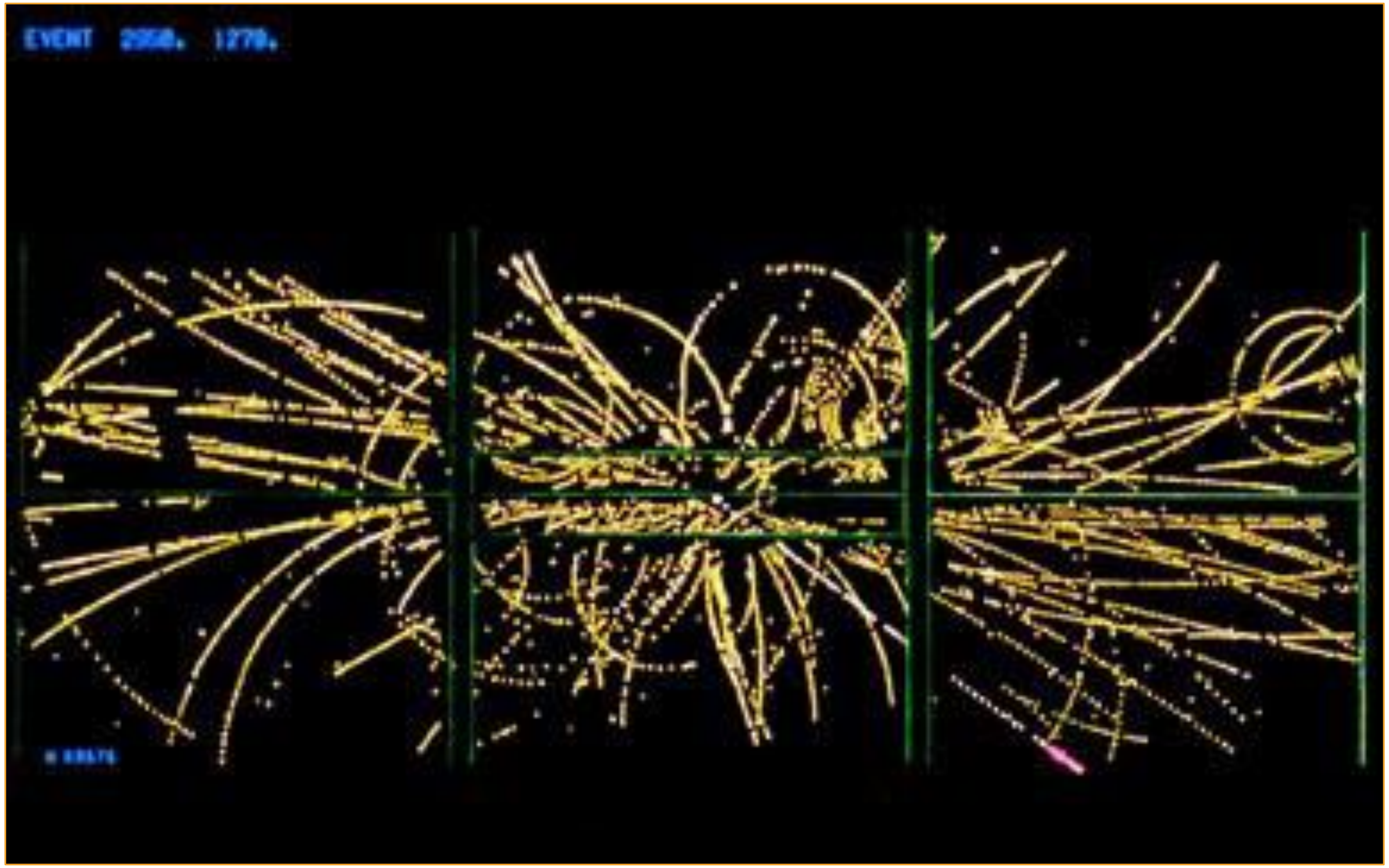


$Z \rightarrow \mu^+\mu^-$



W event in UA2





First observations and mass measurements

1980's : CERN produces a lot of Z's and W's

Collisions $p + \bar{p}$ @ 540 GeV

Measures: Life time, masses, decay rates, …

Fine tests of weak interaction

$m_{W^\pm} = 82.1 \pm 1.7$ GeV

$m_{Z^0} = 93.0 \pm 1.7$ GeV

But no mass terms in the Lagrangian for intermediate bosons to preserve gauge invariance, but experimentally they have mass!

The introduction of mass terms would cause an explicit break in symmetry.

Gauge transformation for vector bosons $A^\mu \rightarrow A^\mu + \partial^\mu \alpha(x)$

$$\frac{{m_A}^2}{2} A^\mu A_\mu \rightarrow \frac{m_A^2}{2} (A^\mu + \partial^\mu \alpha(x))\big(A_\mu + \partial_\mu \alpha(x)\big) \neq \frac{m_A^2}{2} A^\mu A_\mu$$

Vector bosons have to be massless.

The solution: introduction of a spontaneous symmetry breaking mechanism, which gives masses to the heavy bosons and lets QED exact symmetry .

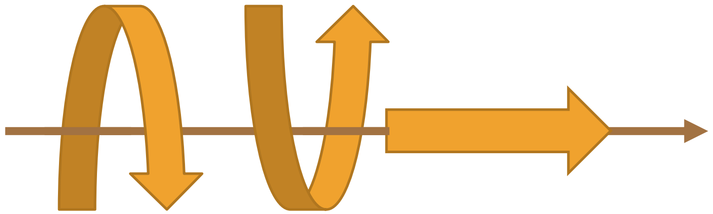
Mass terms for gauge bosons

Mass correlated with polarisation and number of degrees of freedom:

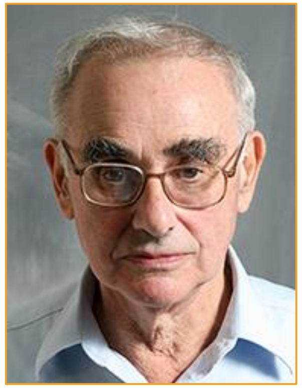
For a spin s, a massive particle has 2s+1 possible spin projections whereas a massless particle has only 2s possible spin projections

Spin 1, i.e. spin is a four-vector but one degree of freedom is « taken » by gauge invariance: three possible polarisations transverse and longitudinal

If mass is null another degree of freedom is forbidden by special relativity



Goldstone theroem
spontaneous symmetry breaking



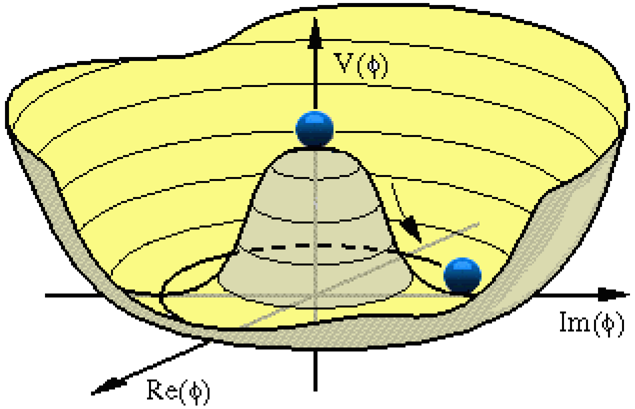
Usual in condensed matter physics.

At high temperature (or energy), matter is in a state having all the symmetries of the equations describing the motion of particles. At low temperature, matter may be in a state that does not have all of the symmetries of the microscopic equations, but only a subset of the complete symmetry group.

In magnetic devices (ferromagnetic, antiferromagnetic…), the rotational symmetry SO(3) of the magnetic moments is spontaneously broken.

When the broken symmetry is a continuous symmetry, a massless particle, a Goldstone boson, appears.

BEGHHK mechanism
Brout-Englert-Guralnik-Hagen-Higgs-Kibble



In $SU(2)_L$ introduction of a complex doublet of scalar fields $\Phi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} = \begin{pmatrix} \frac{\varphi_1 + i\varphi_2}{\sqrt{2}} \\ \frac{\varphi_3 + i\varphi_4}{\sqrt{2}} \end{pmatrix}$

Add the « Higgs part » into the lagrangian $\mathcal{L}_H = (D^\mu \Phi)^\dagger (D_\mu \Phi) - V(\Phi^\dagger \Phi)$

with $\boldsymbol{V(\Phi^\dagger \Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2}$ $\mu^2, \lambda > 0$

Vacuum / $\frac{\partial V}{\partial \Phi^\dagger \Phi} = 0 \Rightarrow \Phi^\dagger \Phi|_{vac.} = \frac{\mu^2}{2\lambda}$

$\Phi_0 = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$ (to keep $U(1)_{EM}$ exact)

Vacuum expectation value of the Higgs field v / $v^2 \equiv \frac{\mu^2}{\lambda}$

Choice of a fundamental state

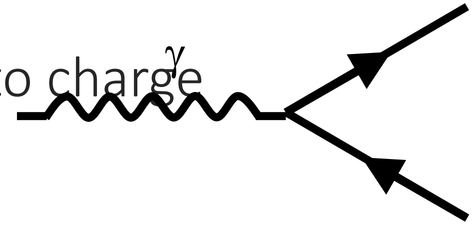
= spontaneous symmetry breaking.

Four scalar bosons:
- three massless Goldstone bosons = three degrees of freedom for the three weak interaction gauge bosons.
- Photon remains massless
- A scalar boson, Higgs, of unpredicted mass...

A scalar Higgs field with a non-zero ground state...
Even before Higgs boson discovery highly testable theory and renormalizable

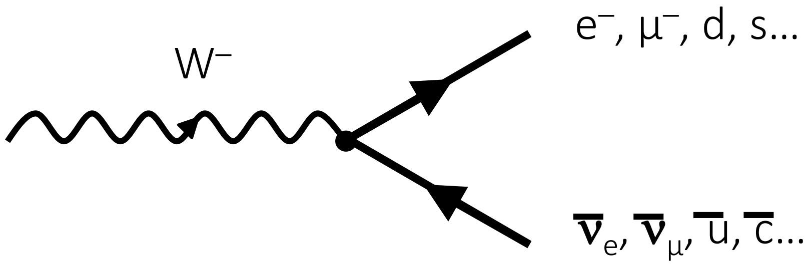
SU(2) ⊗ U(1) + Higgs
1967 electroweak sector

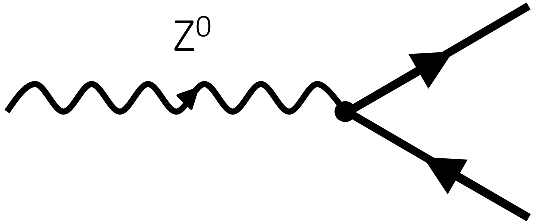
Photon, electromagnetic mediator, coupling proportionnal to charge



Particle/antiparticle pairs for particle with electric charge

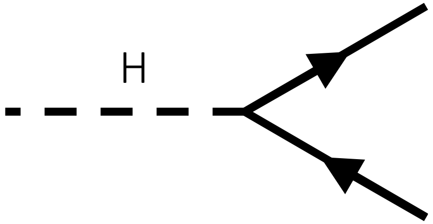
Massive $W^{\pm}$ and Z^0, weak interaction mediators





All particle/antiparticle pairs including ν,$W^{\pm}$

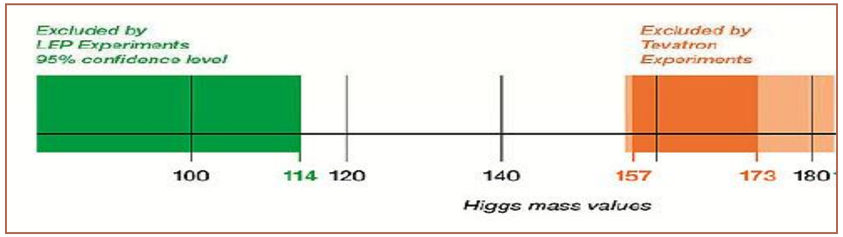
Higgs boson, coupling proportionnal to particle mass

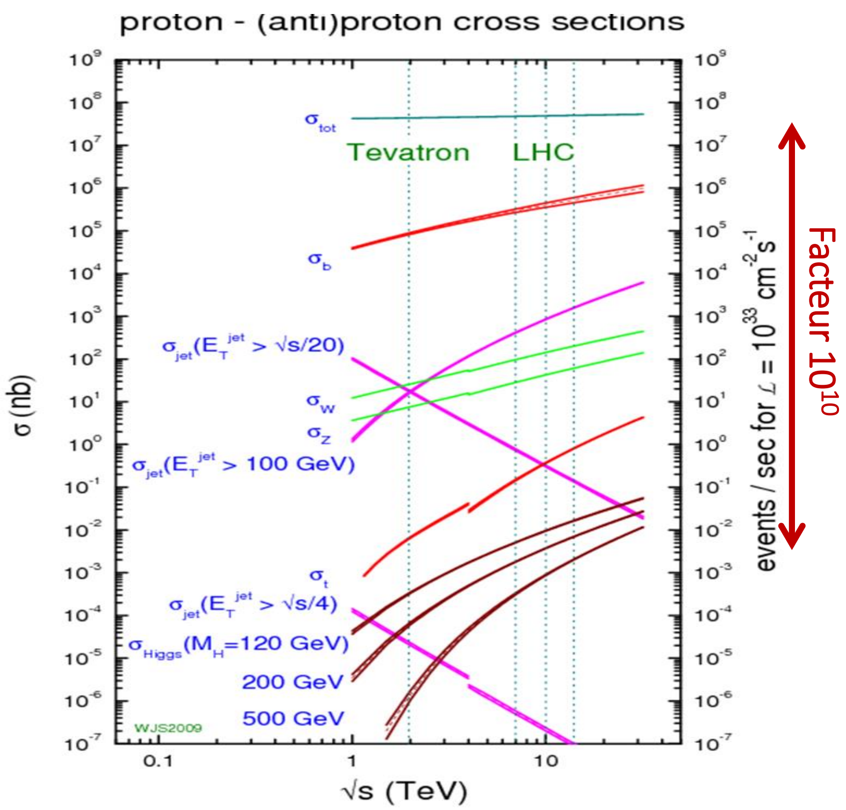


All particle/antiparticle pairs including H,Z,$W^{\pm}$

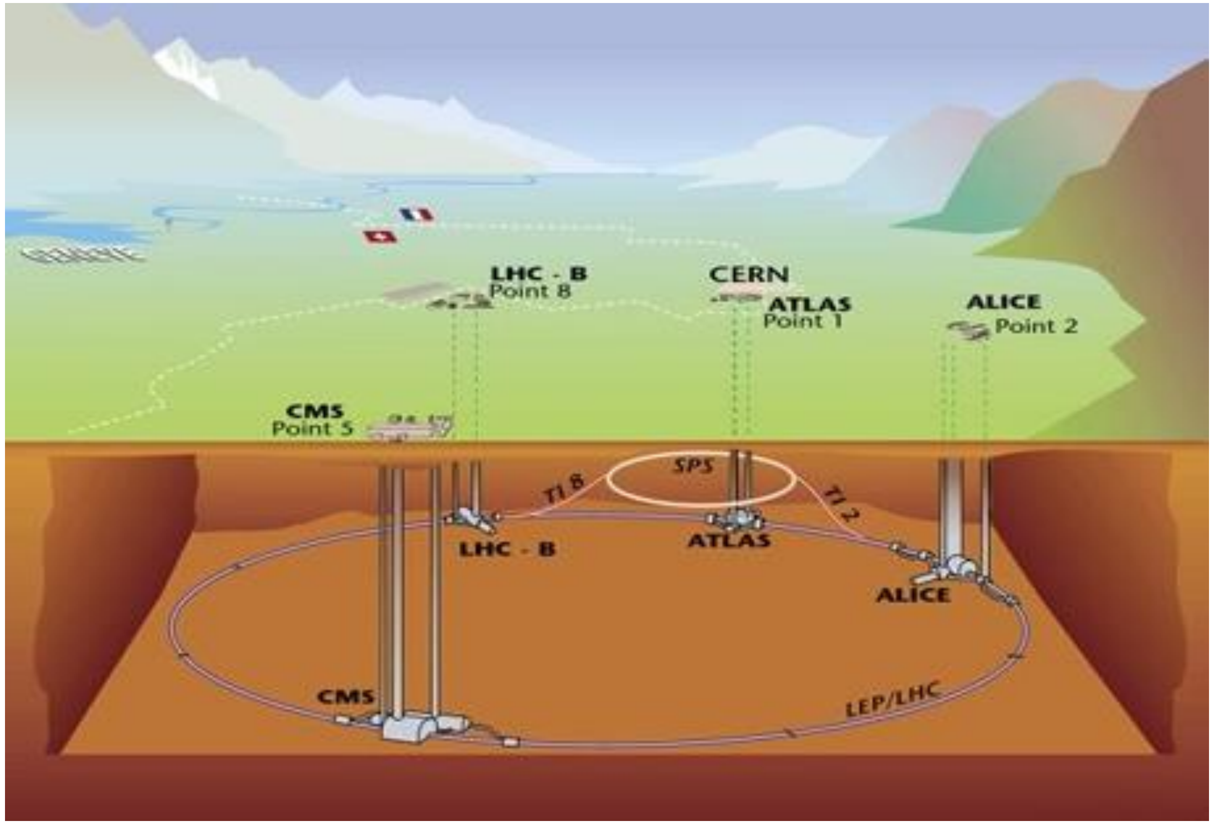
And Feynman rules for electroweak theory

Higgs boson discovery





⇒ Collider requirements: high energy and high luminosity

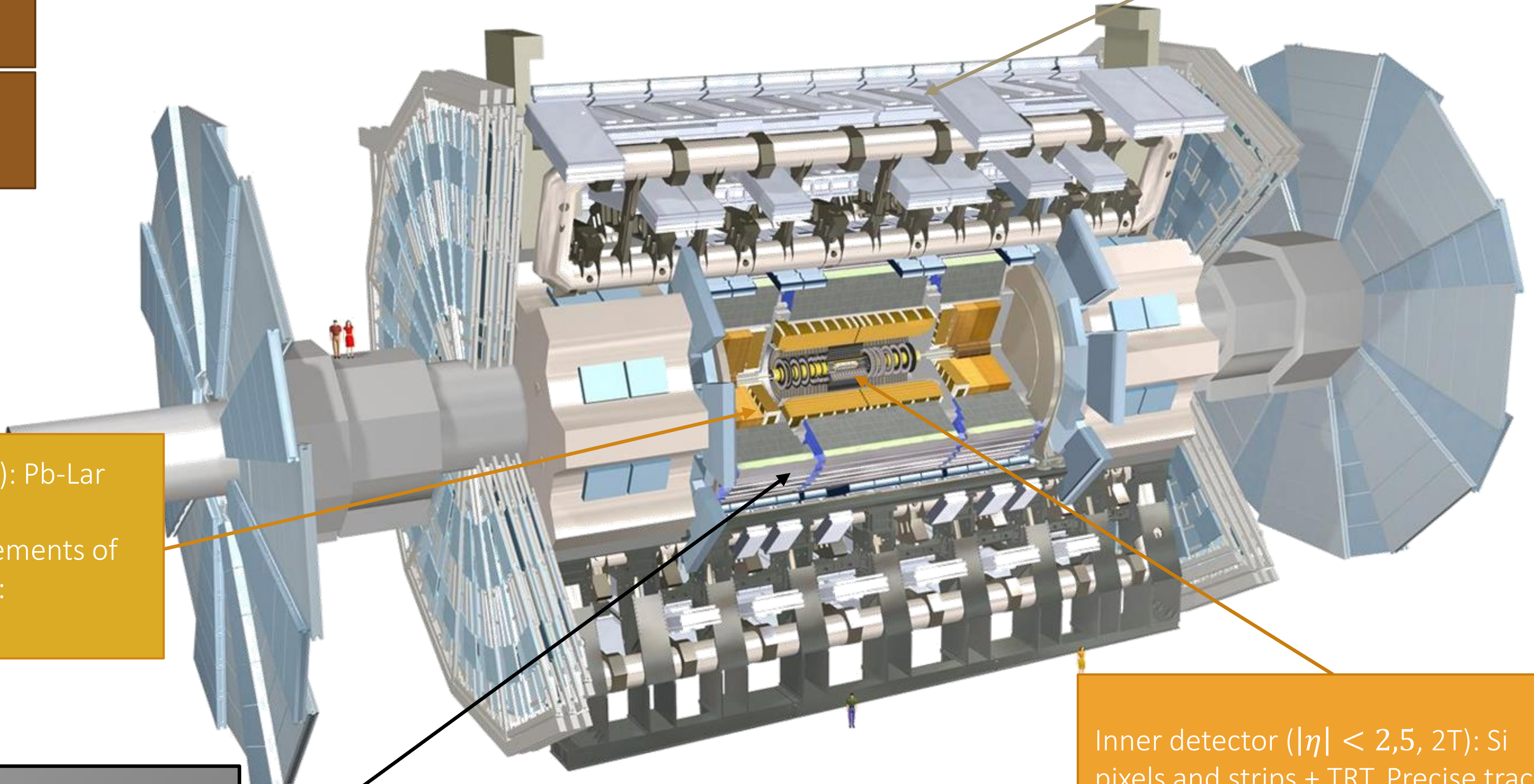


ATLAS EXPERIMENT

Length: 46 m
Diameter: 25 m
Weight: 7000 t
channels: ~ 90 000 000

3 level trigger:
40 MHz $\rightarrow$ ~ 200 Hz

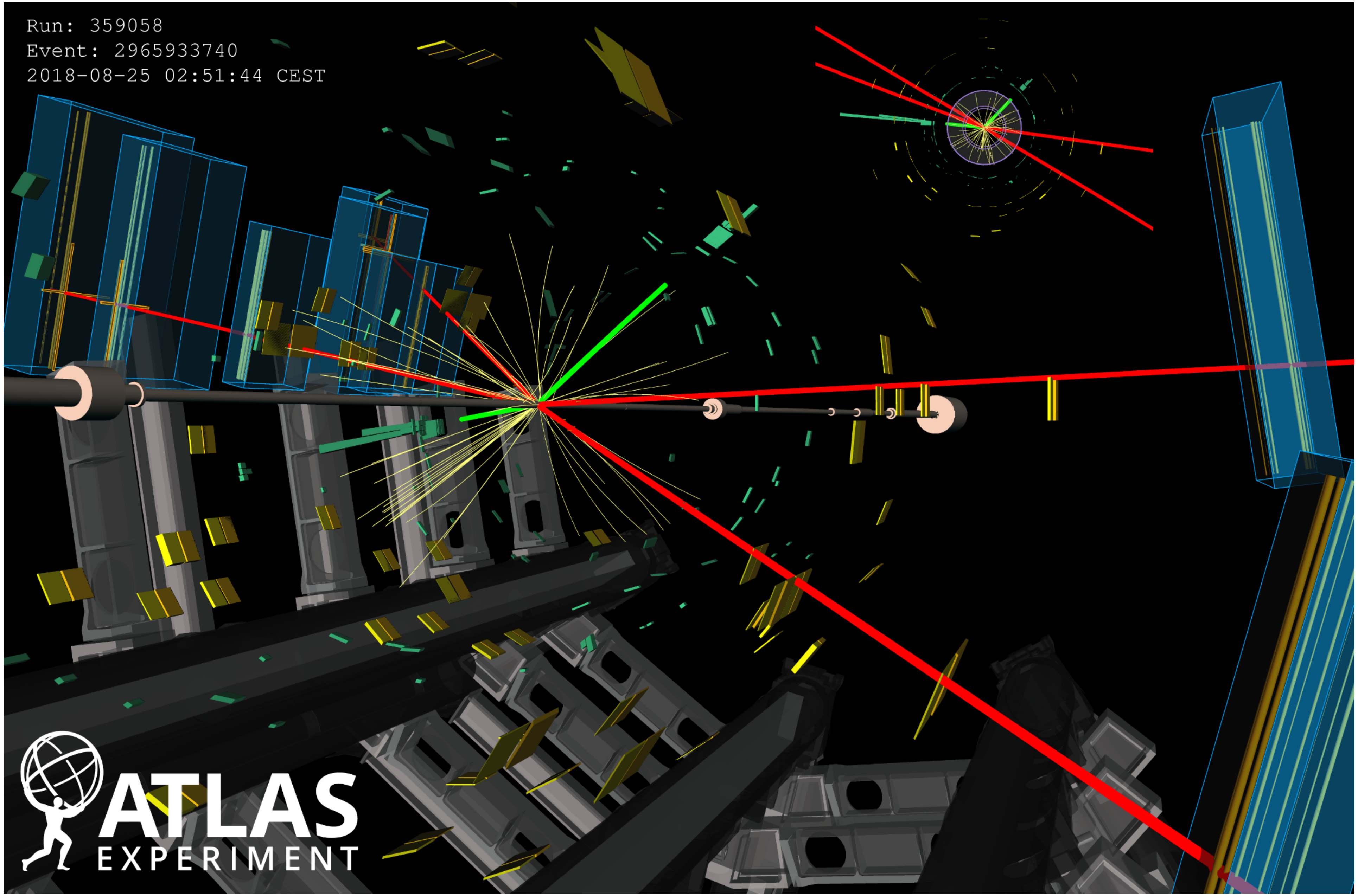
Muon spectrometer ($|\eta| < 2{,}7$): air toroïdal magnet + muon chambers. Trigger, identification and muon measurements. Resolution in p_T: ~ 10% at 1 TeV



EM calorimeter ($|\eta| < 3{,}2$): Pb-Lar accordion shaped. trigger, identification and measurements of e/γ. Resolution in energie: $\sigma(E)/E \sim 10\%/\sqrt{E(GeV)}$

Hadronic calorimeters ($|\eta| < 4{,}9$): Fer/scintillators and Cu/W-Lar. Trigger and measurements of jets and missing E_T. Energy resolution: $\sigma(E)/E = 50\%/\sqrt{E(GeV)} \oplus 0{,}03$

Inner detector ($|\eta| < 2{,}5$, 2T): Si pixels and strips + TRT. Precise track and vertex + separation e/π. Resolution in p_T: $\sigma/p_T \sim 3{,}8\ 10^{-4}\ p_T\ (GeV) \oplus 0{,}015$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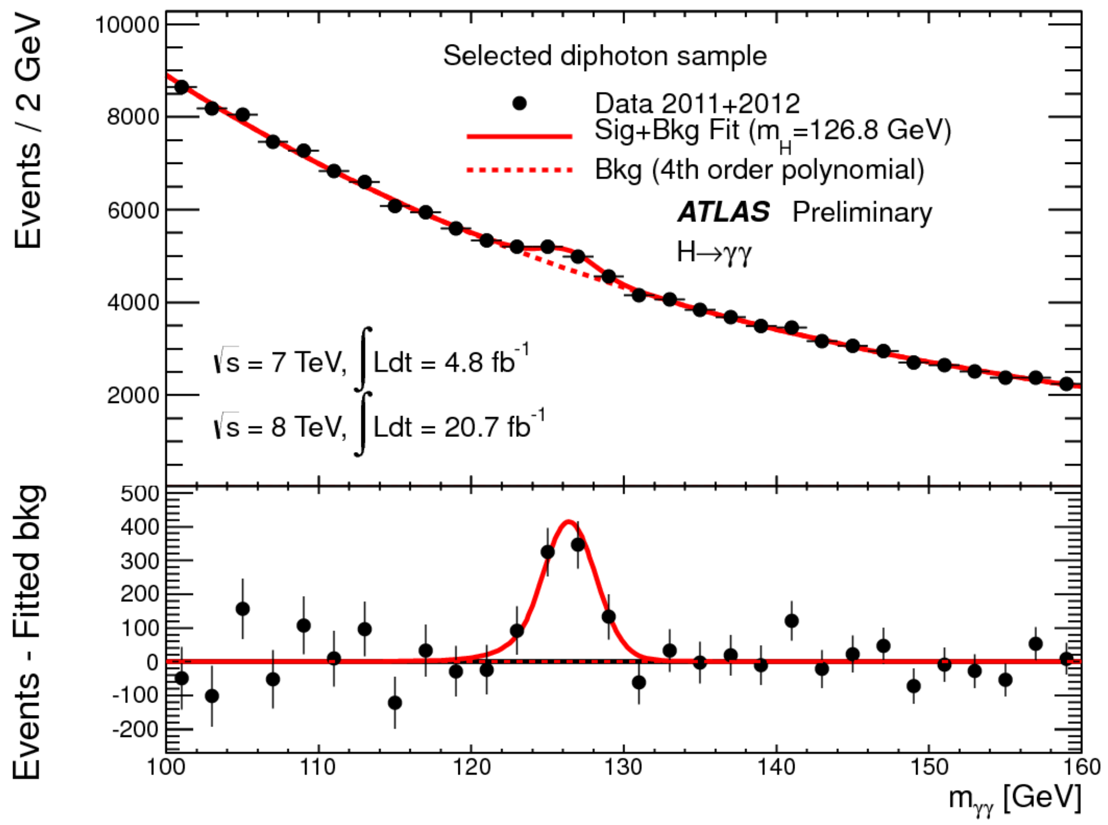
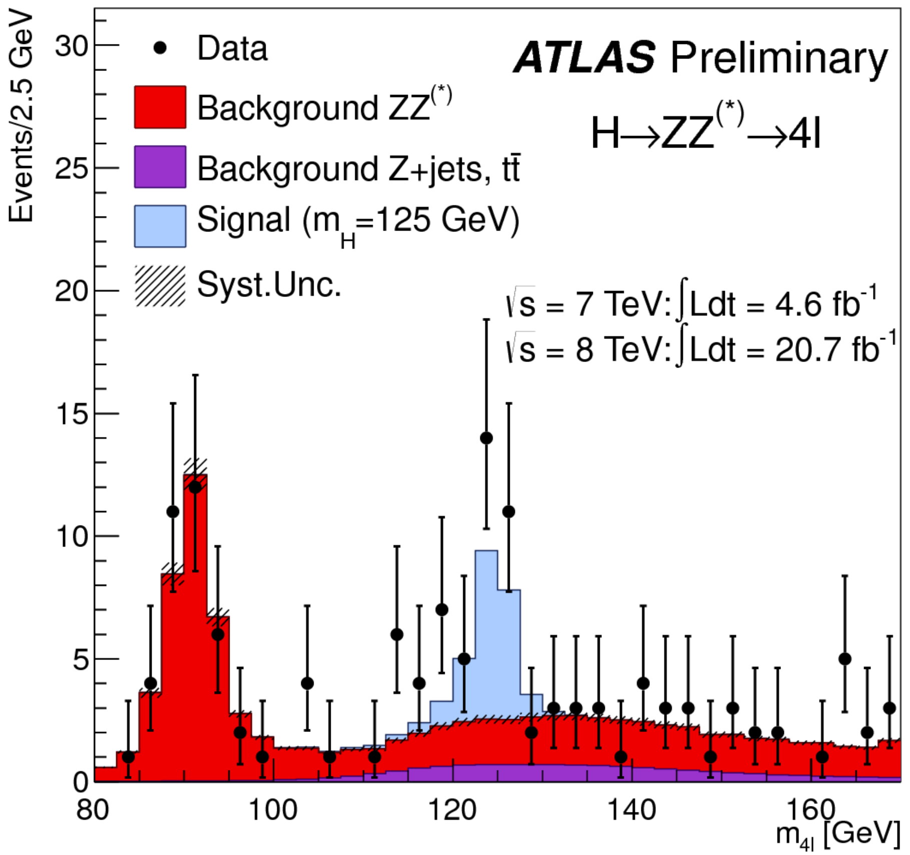
EXPERIMENT

2012 discovery H→γγ channel



2012 discovery $H \to ZZ^* \to 4\ell$ channel




2013 NOBEL PRIZE IN PHYSICS
François Englert
Peter W. Higgs
© © The Nobel Foundation. Photo: Lovisa Engblom.
ALFR. NOBEL
"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

What did we learn?

EW unification has many implications:

Before a phase transition sometimes in the history of the very early Universe, electric, magnetic and weak interactions were unified, and described by the same symmetry group

There exists a neutral boson, Z

Many relations between parameters, which can be checked experimentally

It is a renormalisable theory

Weak bosons are massive

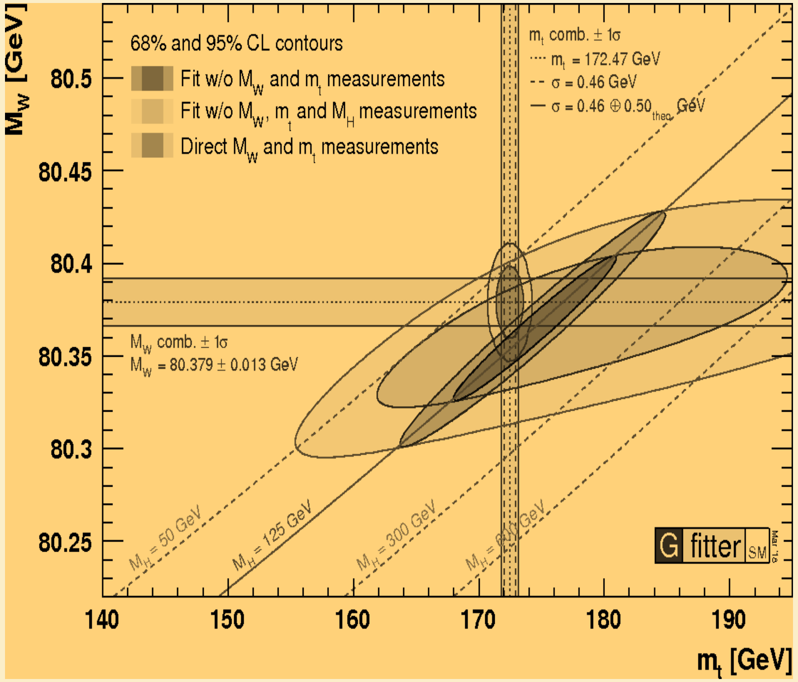
EWSB:

U(1)EM exact, massless vector boson, $SU(2)_L$ Weak with three massive vectors bosons

One scalar massive boson

Fermions masses through Yukawa couplings

Experimental tests of the standard model of particle physics

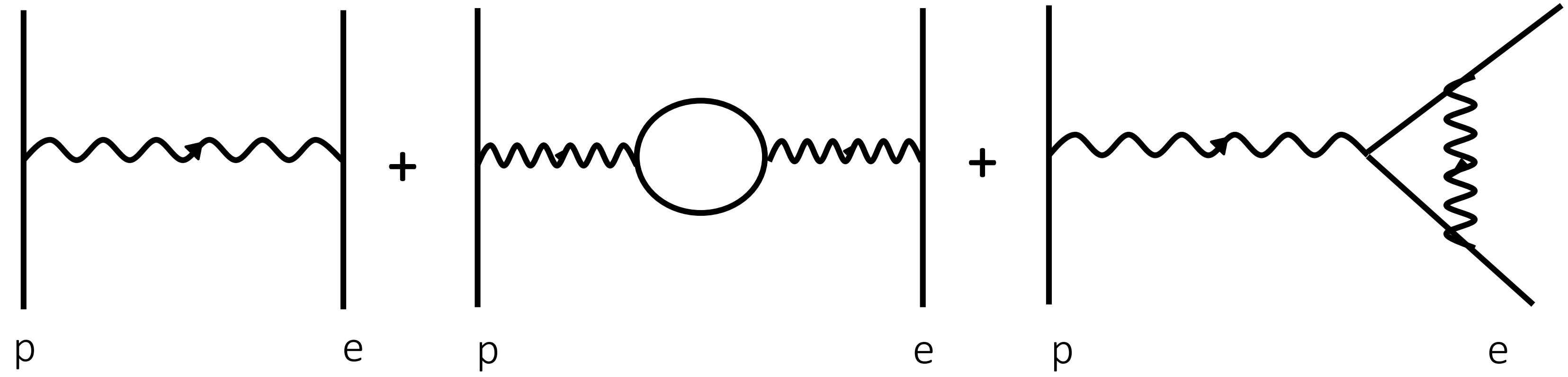


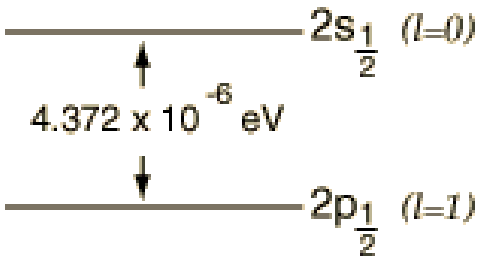
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \psi_i\gamma_{ij}\psi_j\phi + h.c. + \left|D_\mu\phi\right|^2 - V(\phi)$$

1. QED Lamb shift

Hydrogen fine structure:

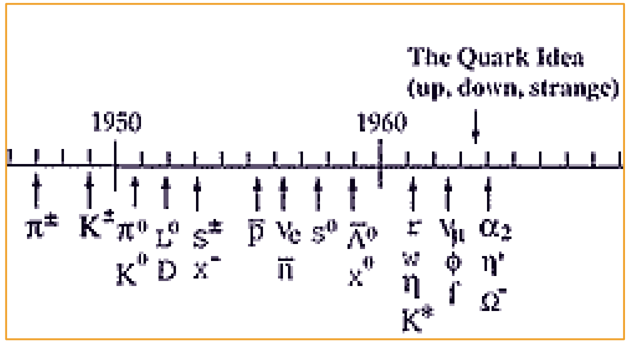
The electron charge is screened by the virtual e^+e^- pairs, so there is a change in charge at small distances and QED predicts a shift between the $2s^1/_2$ and $2p^1/_2$ H atom levels predicted at the same energy by Schrödinger's equation

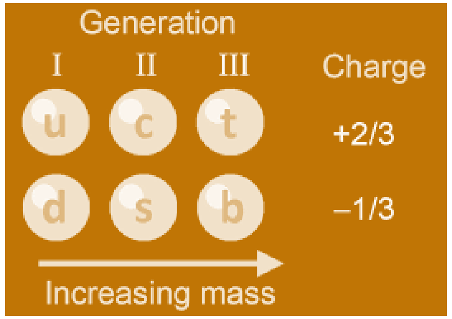




ΔE_{th} = 1057,864 ± 0,014 MHz ©1997
ΔE_{exp} = 1057,862 ± 0,020 MHz ©1997

2. QCD color



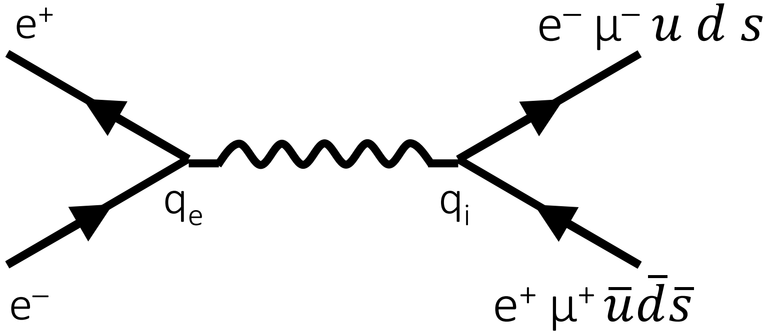


What about the Δ^{++} spin 3/2 baryon (uuu) (↑↑↑)?

1965 introduction of the color quantum number

Experimentally :

$R_{had} = \sigma(e^+e^- \to \text{had.}) / \sigma(e^+e^- \to \mu^+\mu^-) = \frac{\sum \sigma_{q\bar{q}}}{\sigma_{\mu^+\mu^-}} = \sum \left(\frac{q_q}{e}\right)^2$ if no colour number



For u, d, s, expected 2/3 observed 2

For u, d, s, c expected 10/9 observed 10/3 etc…

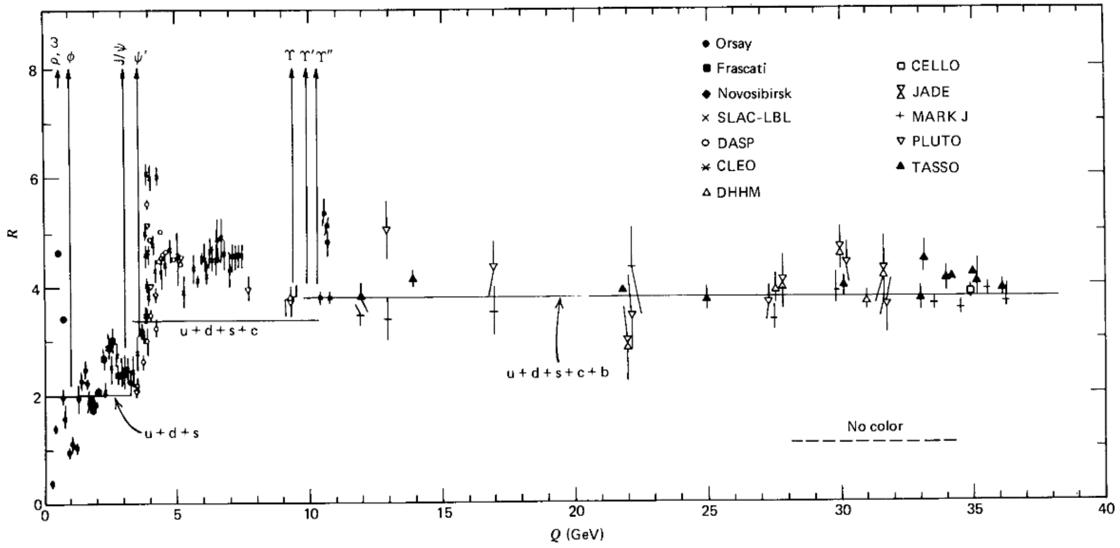
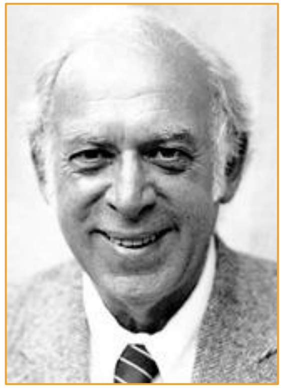
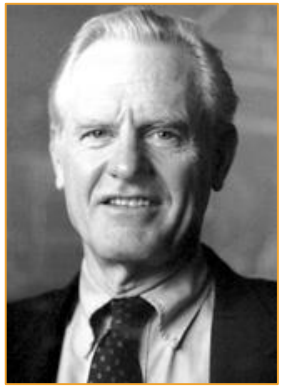


Fig. 11.3 Ratio R of (11.6) as a function of the total e^-e^+ center-of-mass energy. (The sharp peaks correspond to the production of narrow 1^- resonances just below or near the flavor thresholds.)

$$R_{had} = 3 \sum \left(\frac{q_q}{e}\right)^2$$

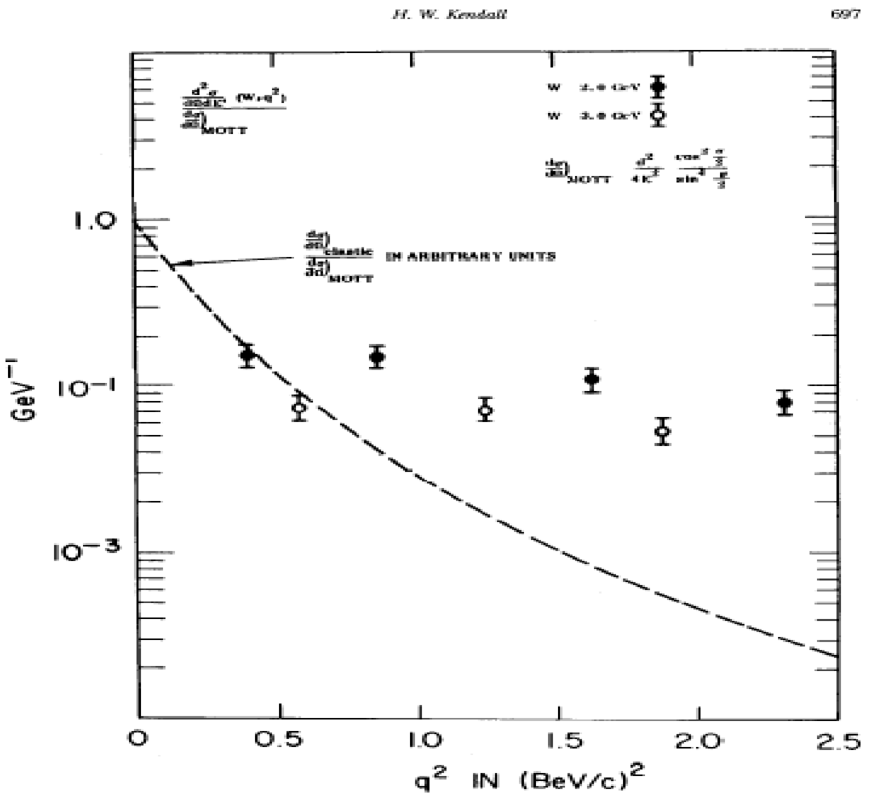
N_c

3. QCD quarks

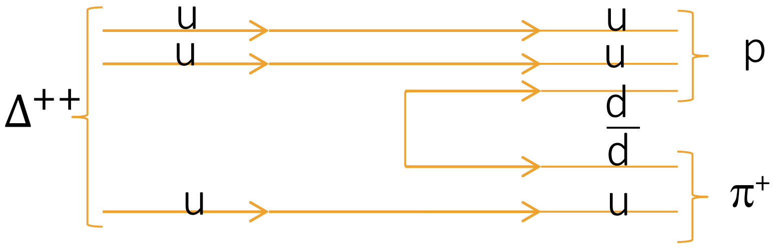

1969: Friedman, Kendal, Taylor (et al.) see a deviation in the scattering of electrons on protons that can be explained by the existence of "partons" in the proton. Like Rutherford's experiment proving existence of nucleus.

Protons have a "structure“: quarks



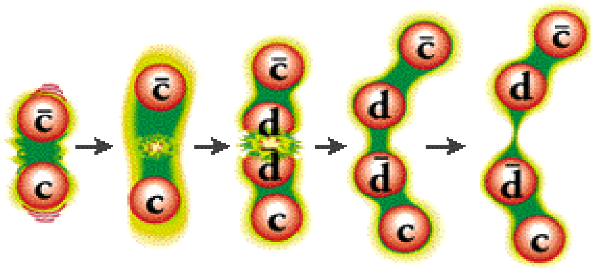
At SLAC, 2 miles linear accelerator with 20 GeV electrons.

Example of strong decay at quark level $\Delta^{++} \rightarrow p + \pi^{+}$

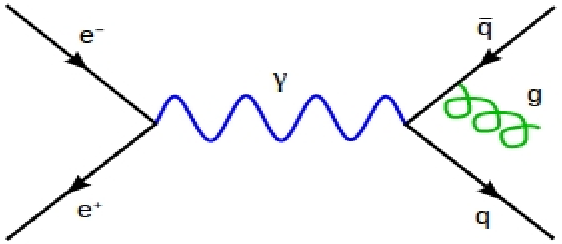


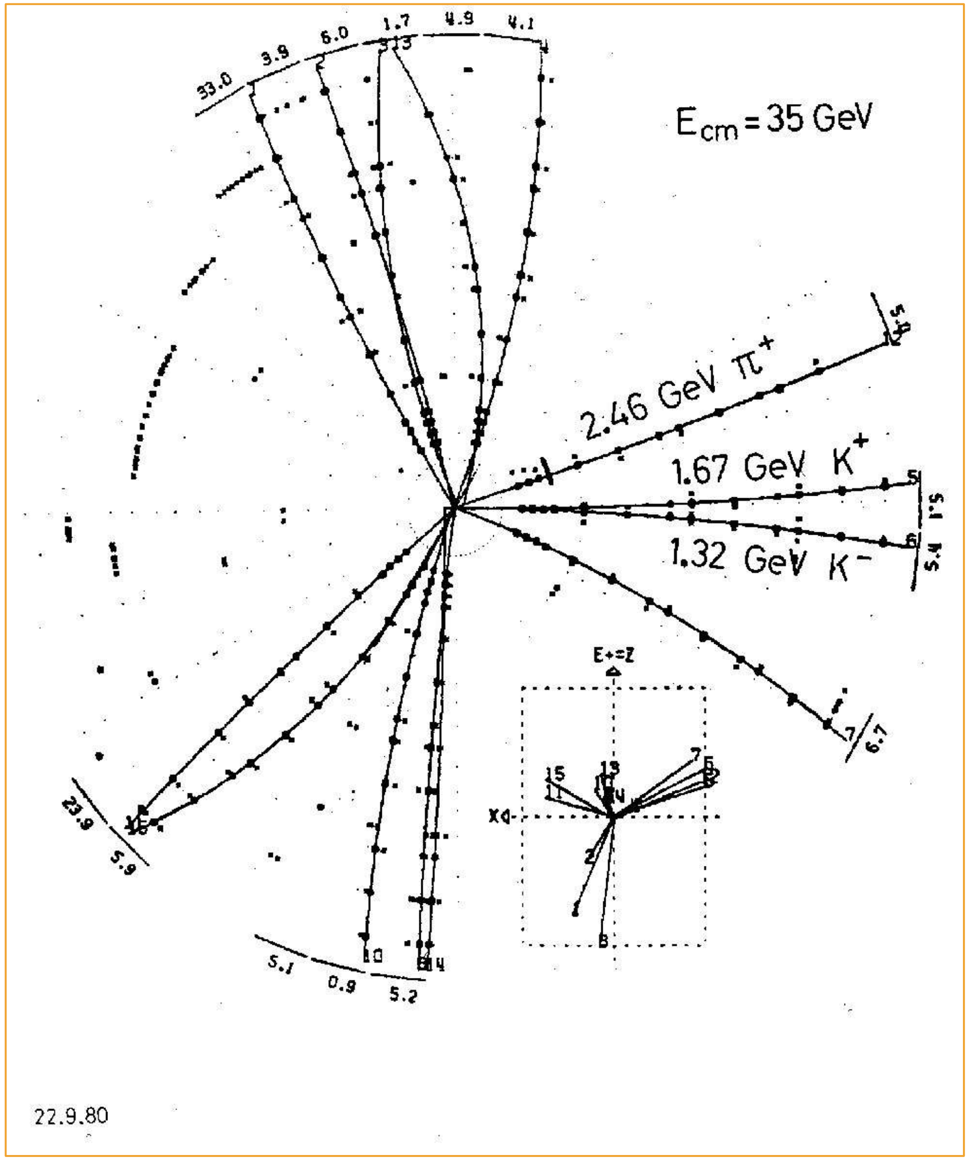
4. QCD gluons

Gluon self-coupling ⇒ no free quark but jets.



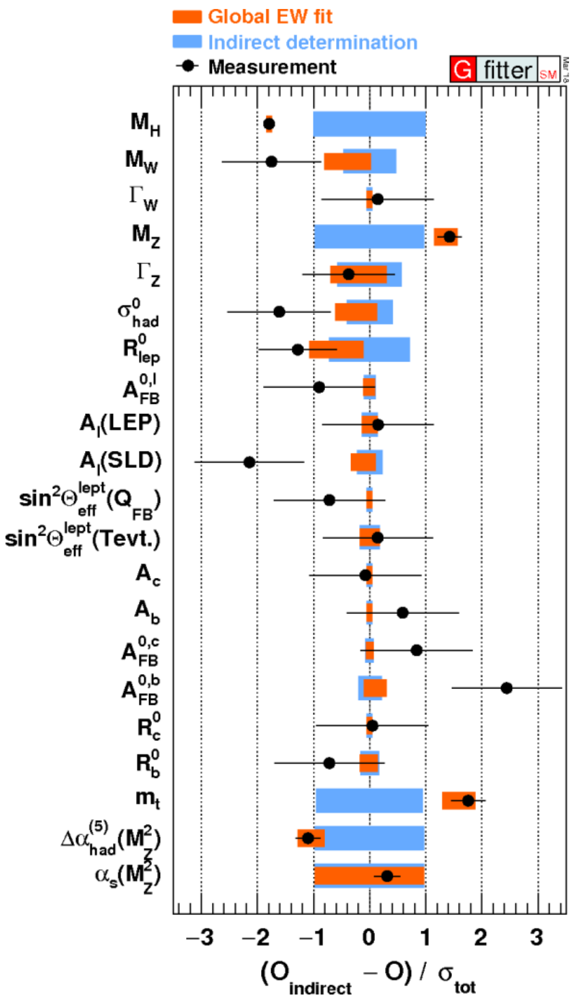
At DESY in 1979, at the PETRA collider, four detectors MARK J, PLUTO, TASSO and JADE @ collision energies of 27 GeV.

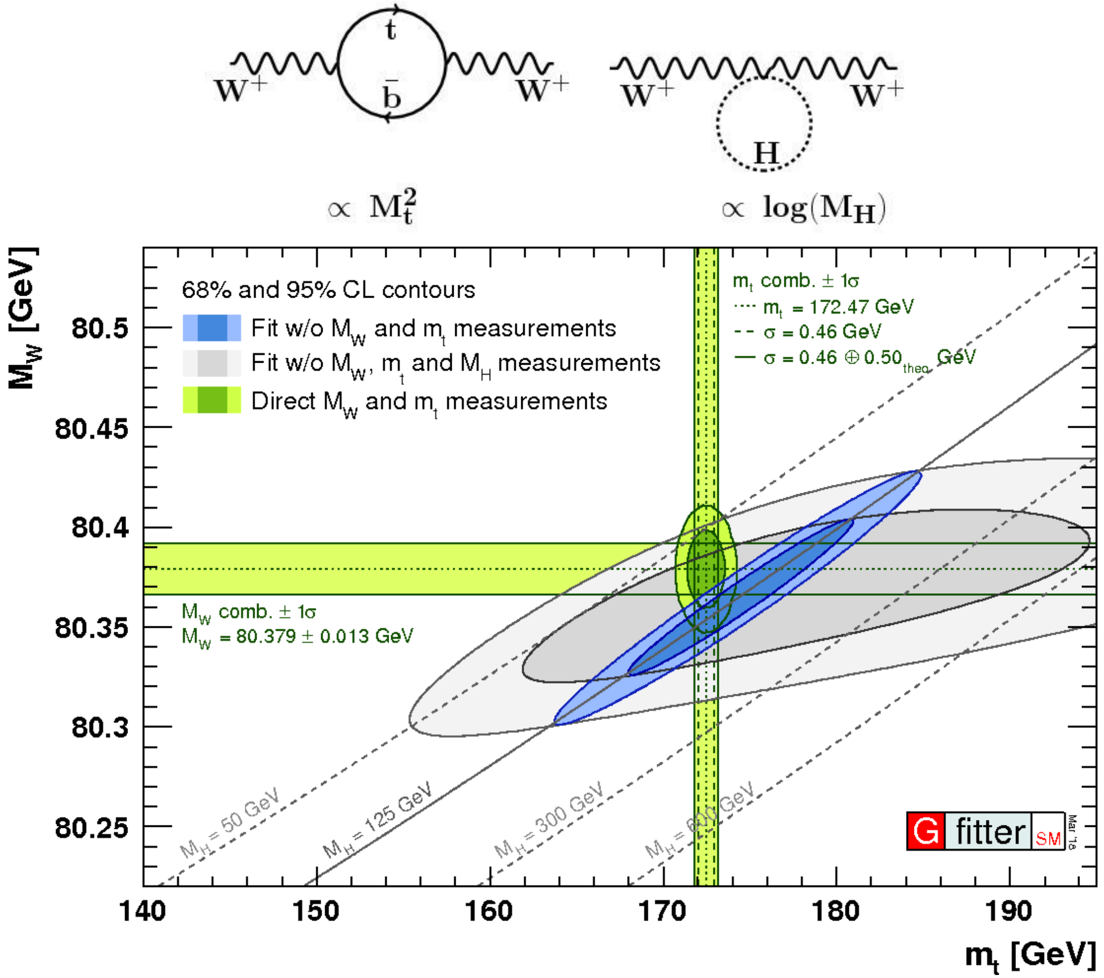




6. Internal consistency of the SM

Global fits of the standard model consistent to within 3 standard deviations or fits with a subset of parameters



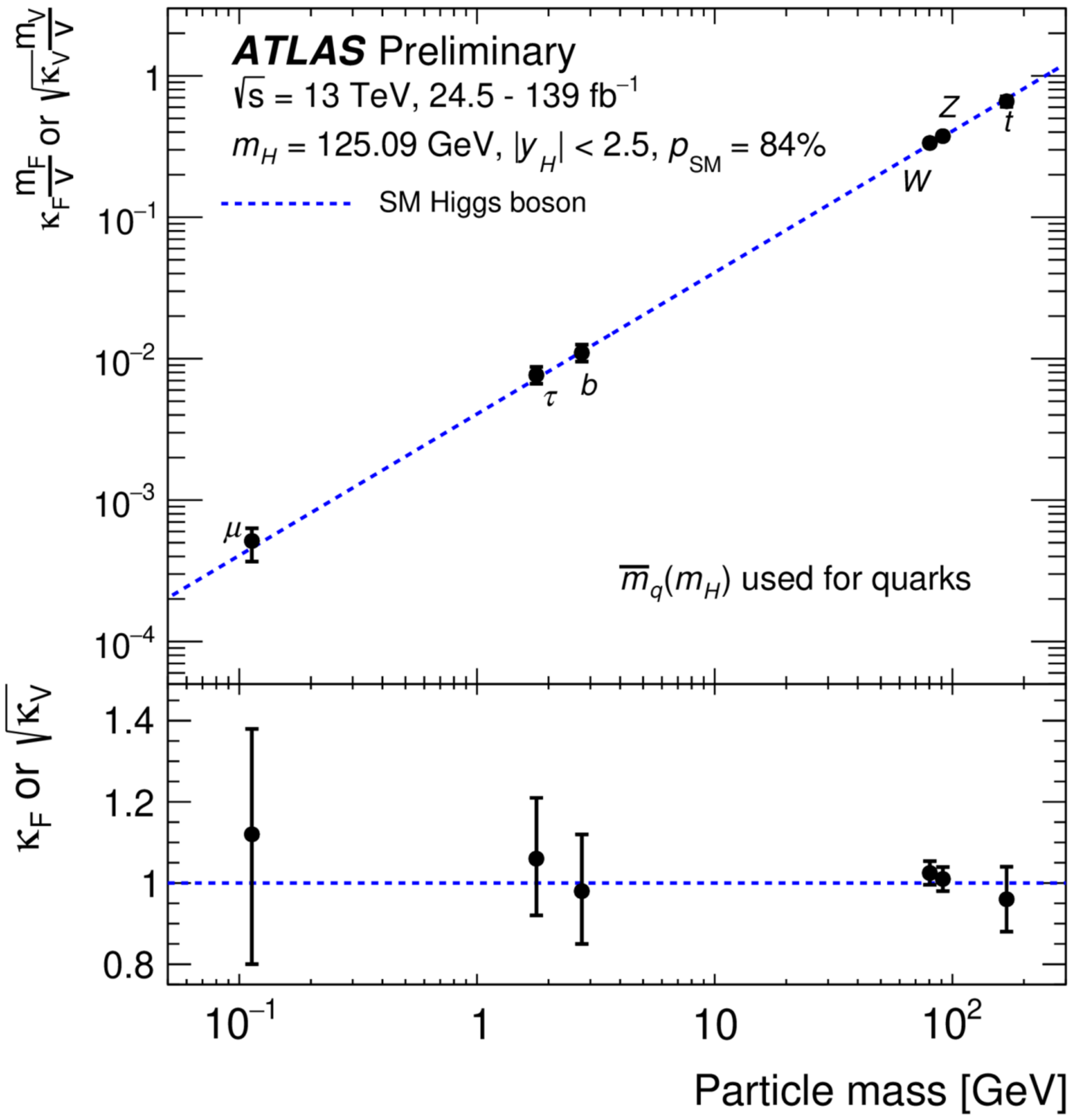


7. Higgs mechanism

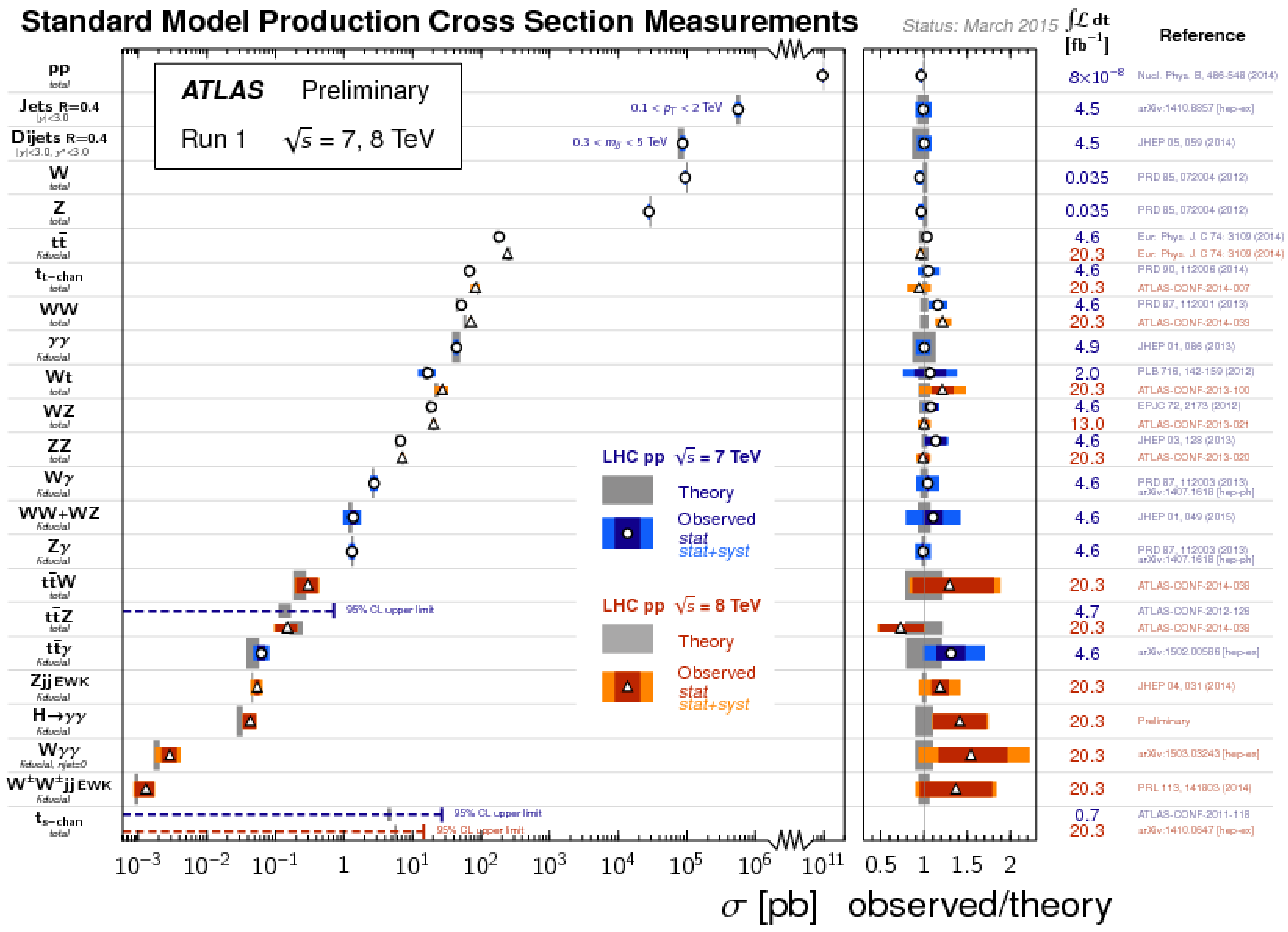
$$M_W = \frac{gv}{2}$$

$$M_Z = \frac{\sqrt{g^2+g'^2}}{2}v$$

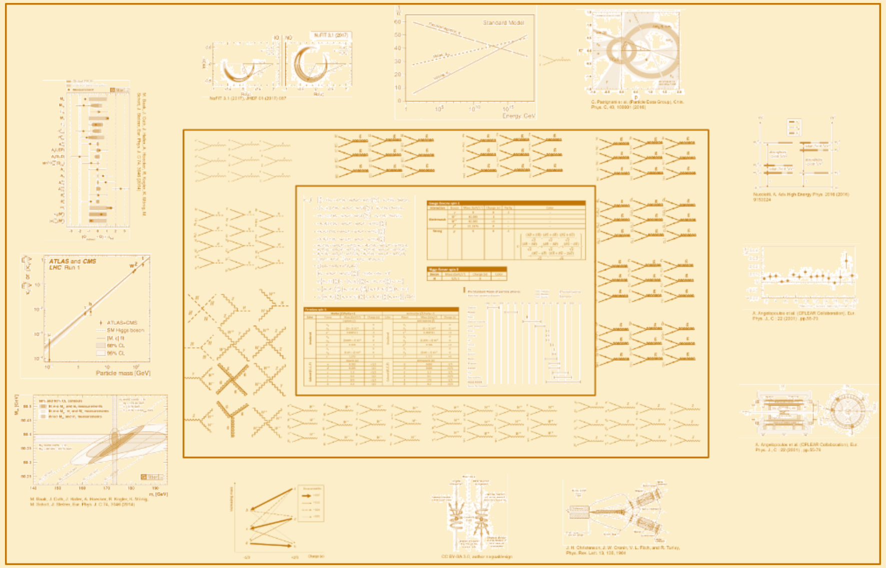
$$m_f = \frac{v}{\sqrt{2}}Y^f$$



8. All cross-sections



Is the Standard Model the ultimate theory?



Fermions

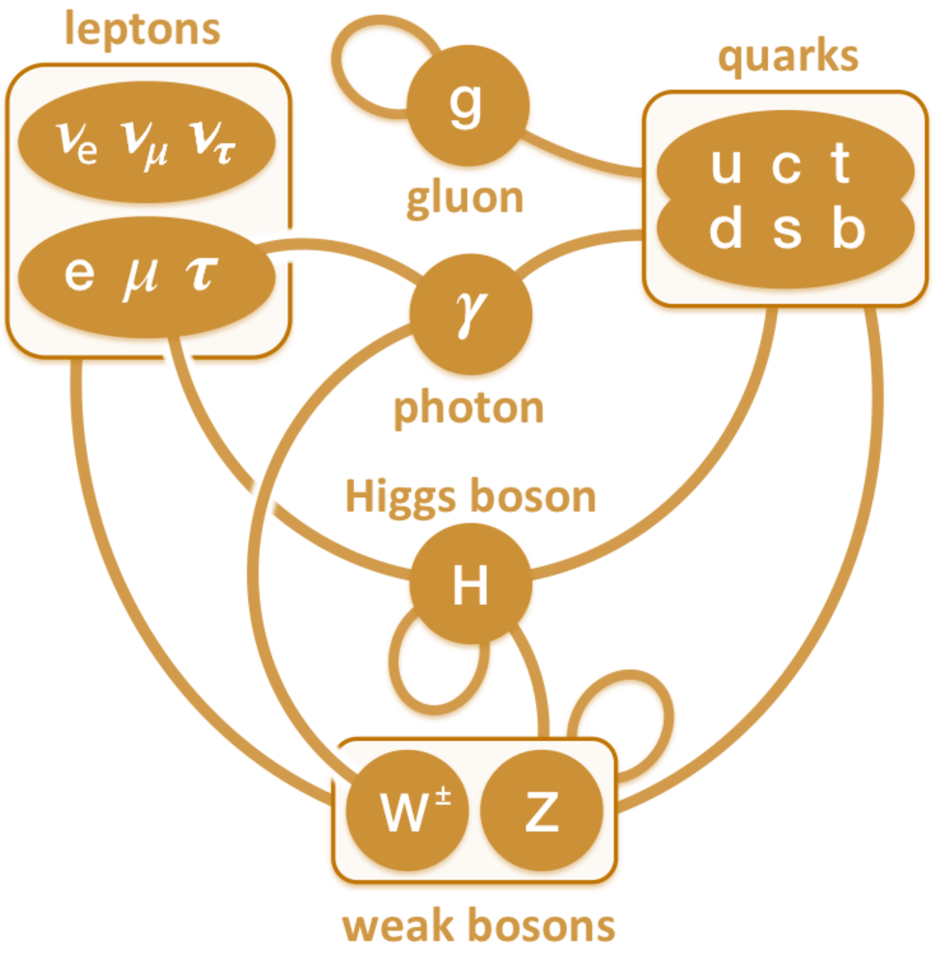
Fermions spin ½							
Matter (f) Parity=+1				Antimatter ($\bar{f}$) Parity=-1			
Color	Flavor	Mass (GeV/c²)	Charge (e)	Color	Flavor	Mass (GeV/c²)	Charge (e)
Uncolored	Leptons (l)			Uncolored	Anti-leptons ($\bar{l}$)		
	ν_e	--	0		$\bar{\nu}_e$	--	0
	ν_1	(0 – 2) 10^{-9}	0		$\bar{\nu}_1$	(0 – 2) 10^{-9}	0
	e^-	0.000511	-1		e^+	0.000511	+1
	ν_μ	--	0		$\bar{\nu}_\mu$	--	0
	ν_2	(0.009 – 2) 10^{-9}	0		$\bar{\nu}_2$	(0.009 – 2) 10^{-9}	0
	μ^-	0.106	-1		μ^+	0.106	+1
	ν_τ	--	0		$\bar{\nu}_\tau$	--	0
	ν_3	(0.05 – 2) 10^{-9}	0		$\bar{\nu}_3$	(0.05 – 2) 10^{-9}	0
	τ^-	1.777	-1		τ^+	1.777	+1
Colored (R, G, B)		Quarks (q)		Colored ($\bar{R}, \bar{G}, \bar{B}$)	Anti-quarks ($\bar{q}$)		
	u	0.002	+2/3		$\bar{u}$	0.002	-2/3
	d	0.005	-1/3		$\bar{d}$	0.005	+1/3
	c	1.3	+2/3		$\bar{c}$	1.3	-2/3
	s	0.1	-1/3		$\bar{s}$	0.1	+1/3
	t	173	+2/3		$\bar{t}$	173	-2/3
	b	4.2	-1/3		$\bar{b}$	4.2	+1/3

Bosons

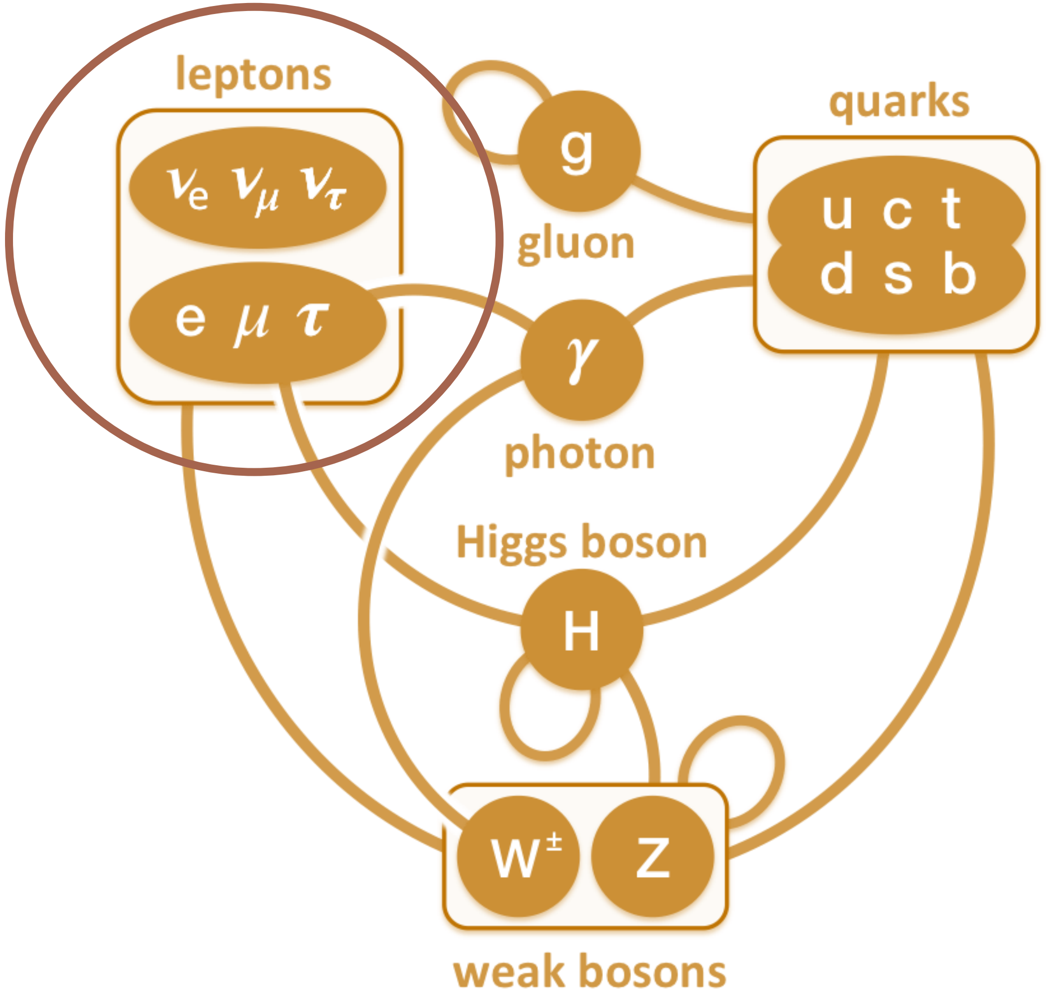
Gauge Bosons spin 1					
Interaction	Boson	Mass (GeV/c²)	Charge (e)	Parity	Color
Electroweak	γ	0	0	-1	--
	W^-	80.385	-1	--	--
	W^+	80.385	+1	--	--
	Z^0	91.1876	0	--	--
Strong	g	0	0	-1	$\in \left\{ \frac{(R\bar{B}+B\bar{R})}{\sqrt{2}}, \frac{(R\bar{G}+G\bar{R})}{\sqrt{2}}, \frac{(B\bar{G}+G\bar{B})}{\sqrt{2}}, \frac{(R\bar{R}-B\bar{B})}{\sqrt{2}}, -i\frac{(R\bar{B}-B\bar{R})}{\sqrt{2}}, -i\frac{(R\bar{G}-G\bar{R})}{\sqrt{2}}, -i\frac{(B\bar{G}-G\bar{B})}{\sqrt{2}}, \frac{(R\bar{R}+B\bar{B}-2G\bar{G})}{\sqrt{6}} \right\}$

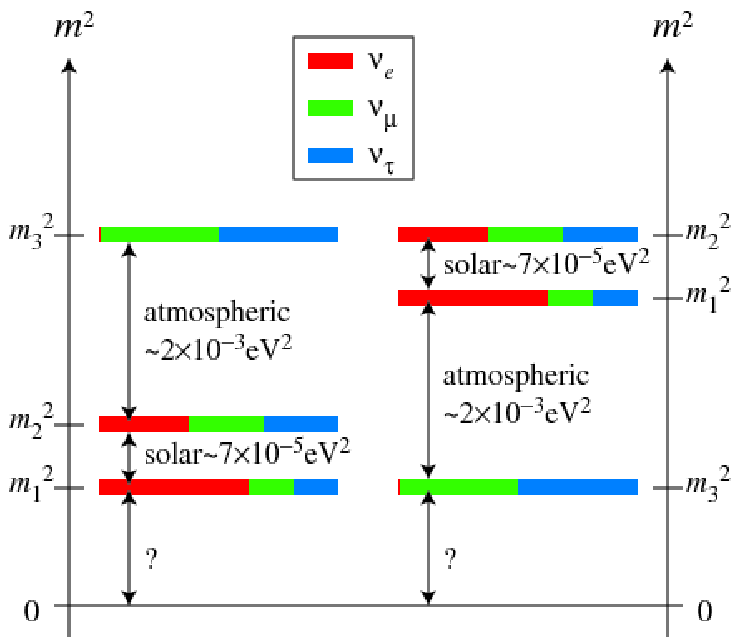
Higgs Boson spin 0			
Boson	Mass (GeV/c²)	Charge (e)	Color
H	125.1	0	--

Interactions

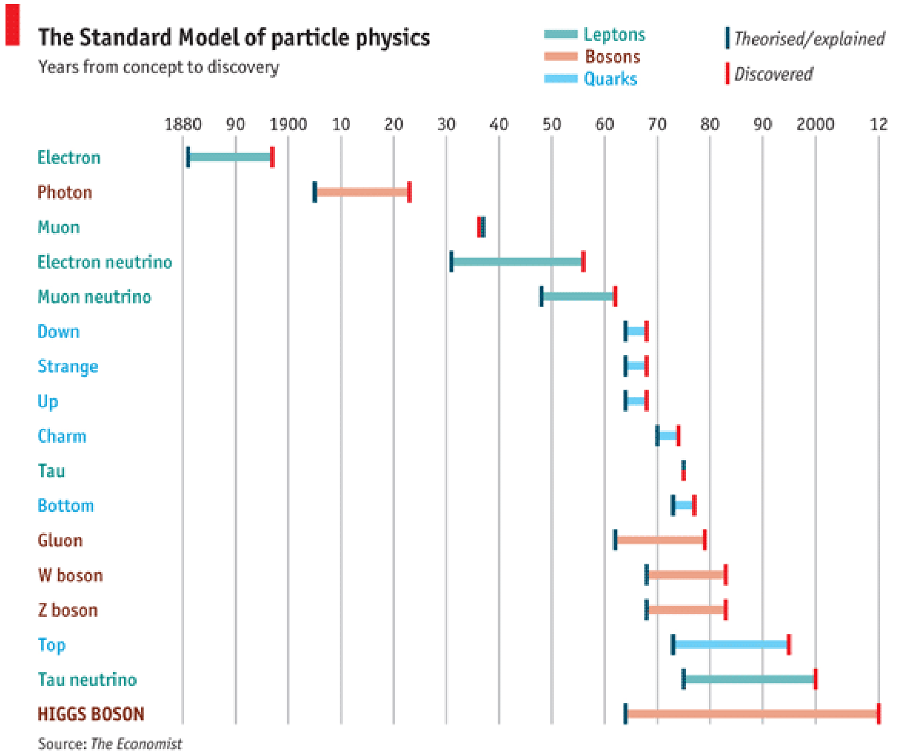


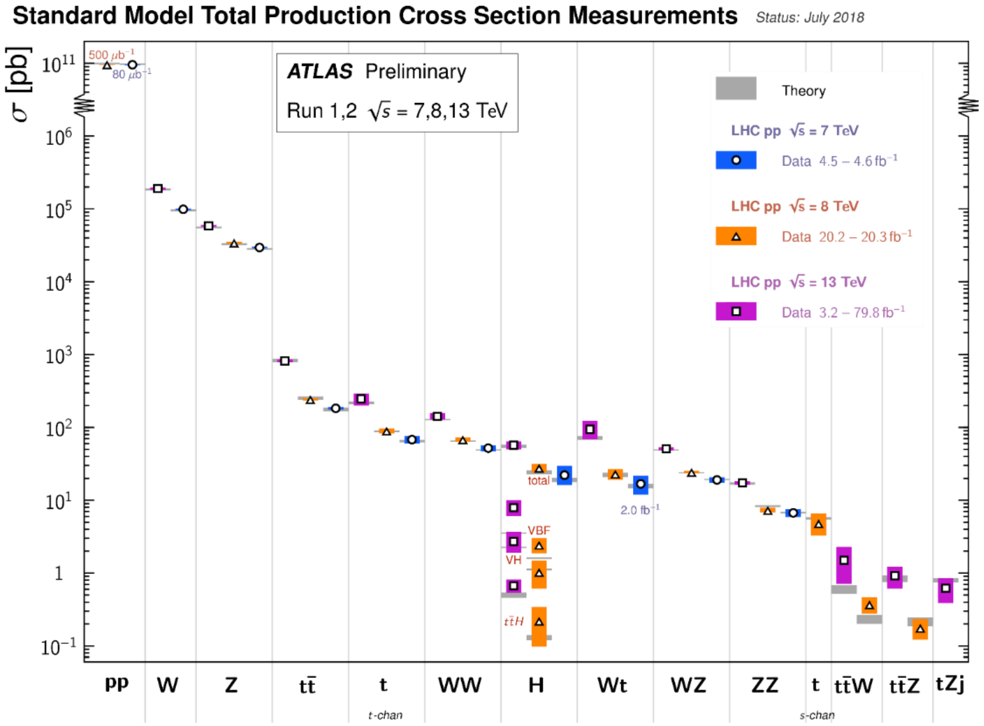
Interactions





Experimentally validated, predictive and robust





A few principles

Every object description (quantum numbers), kinematics and dynamics comes from a very few concepts and principles: energy, quantum mechanics & special relativity, symmetries, local gauge invariance, spontaneous symmetry breaking.

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \psi_i \gamma_{ij} \psi_j \phi + h.c. + \left|D_\mu \phi\right|^2 - V(\phi)$$

As stated by S. Weinberg, it's beautiful because it has a great sense of inevitability.

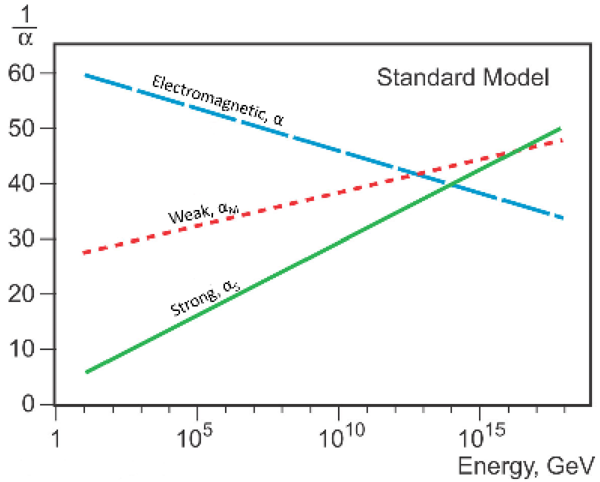
Open questions

Gravitation

Neutrinos

Dark Matter

?



Early Universe

Dark Energy

Antimatter

- Further tests
- Precision measurements
- Look elsewhere (at the other end of the scale, to infinity and beyoooond!)

Future is in your hands

Thanks for your attention