Introduction to Particle Physics

Max Klein

UNIVERSITY OF LIVERPOOL

There are … agents in nature able to make the particles of bodies stick together by very strong attractions. And it is the business of experimental philosophy to find them out

Newton: Opticks (1704)

The creative act depends on private visions and on solitary constructions and always draws on the legacy and the resources of the community – be it in the arts, literature, technology or the science.

Schweber: QED and the Men Who Made It
Dyson, Feynman, Schwinger, Tomonaga (1994)

Introductory Course to High Energy Physics, University of Liverpool, Spring 2013

Remarks and Literature

1. Half semester course – can only introduce concepts, experiments, results, questions and not provide a systematic, mathematical nor technical foundation of HEP

2. Focus on the origin, present and prospects of particle physics, on the electromagnetic, weak and strong interactions, detector and accelerators – no coverage of gravitation and no time for astro-particle physics

3. The course follows no single text book, but please consult for accompanying reference

Particle Physics, B.R. Martin and G. Shaw, Wiley&Sons

Particle Data Book
http://pdg.lbl.gov

History: *The Harvest of a Century*, S. Brandt, Oxford University Press
Facts and Mysteries, M. Veltman, World Scientific [one formula $E=mc^2$]
Experimental: *Elementary Particle Physics*, A. Bettini, Cambridge University Press
Formal: *A Modern Introduction to Particle Physics*, F. Zuddin and R. Zuddin, World Scientific
Quarks and Leptons, F. Halzen and A. Martin, Wiley&Sons
Concepts: *Concepts of Particle Physics*, K. Gottfried and V. Weisskopf, Oxford U Press and Clarendon Press (NY)
Classic Introductions: D. Griffiths, Wiley& Sons also D. Perkins, Oxford University Press (?)
Interesting to read: *Constructing Quarks*, A. Pickering, University of Chicago Press
Learning about Particles, J. Steinberger, Springer
Tabibito, H. Yukawa, World Scientific and many others.
A Zeptospace Odyssey (*A Journey into the Physics of the LHC*) G. Giudice, Oxford University Press, 2010

find YOUR preferred book and enjoy reading about a most fascinating field of modern science

Units

Convention in particle physics:

h = one unit of action (ML^2/T), c = one unit of velocity (L/T)

mass (m), momentum (mc), energy (mc^2) are of dimension [GeV]

length (h/mc), time (h/mc^2) are of dimension [GeV^{-1}]

Conventional Mass, Length, Time Units, and Positron Charge in Terms of $\hbar = c = 1$ Energy Units

Conversion Factor	$\hbar = c = 1$ Units	Actual Dimension
$1\ \text{kg} = 5.61 \times 10^{26}$ GeV	GeV	$\frac{\text{GeV}}{c^2}$
$1\ \text{m} = 5.07 \times 10^{15}\ \text{GeV}^{-1}$	GeV^{-1}	$\frac{\hbar c}{\text{GeV}}$
$1\ \text{sec} = 1.52 \times 10^{24}\ \text{GeV}^{-1}$	GeV^{-1}	$\frac{\hbar}{\text{GeV}}$
$e = \sqrt{4\pi\alpha}$	—	$(\hbar c)^{1/2}$

Remember: 0.2 fm * 1 GeV = 1 ← d*p=ħ, particle physics is high energy physics.
High energies to resolve smallest dimensions and to produce heavy particles

History of Particle Physics*)

Ancient Philosophy – (atomism? particles-fields? ..)

Electron – the first elementary particle, the atom can be split

Atomic Nucleus – scattering experiments and the proton

Beta Decay – the weak interaction and the neutrinos

Partons – order to the hadronic variety with confinement

Charm – the November 1974 revolution, l-q symmetry

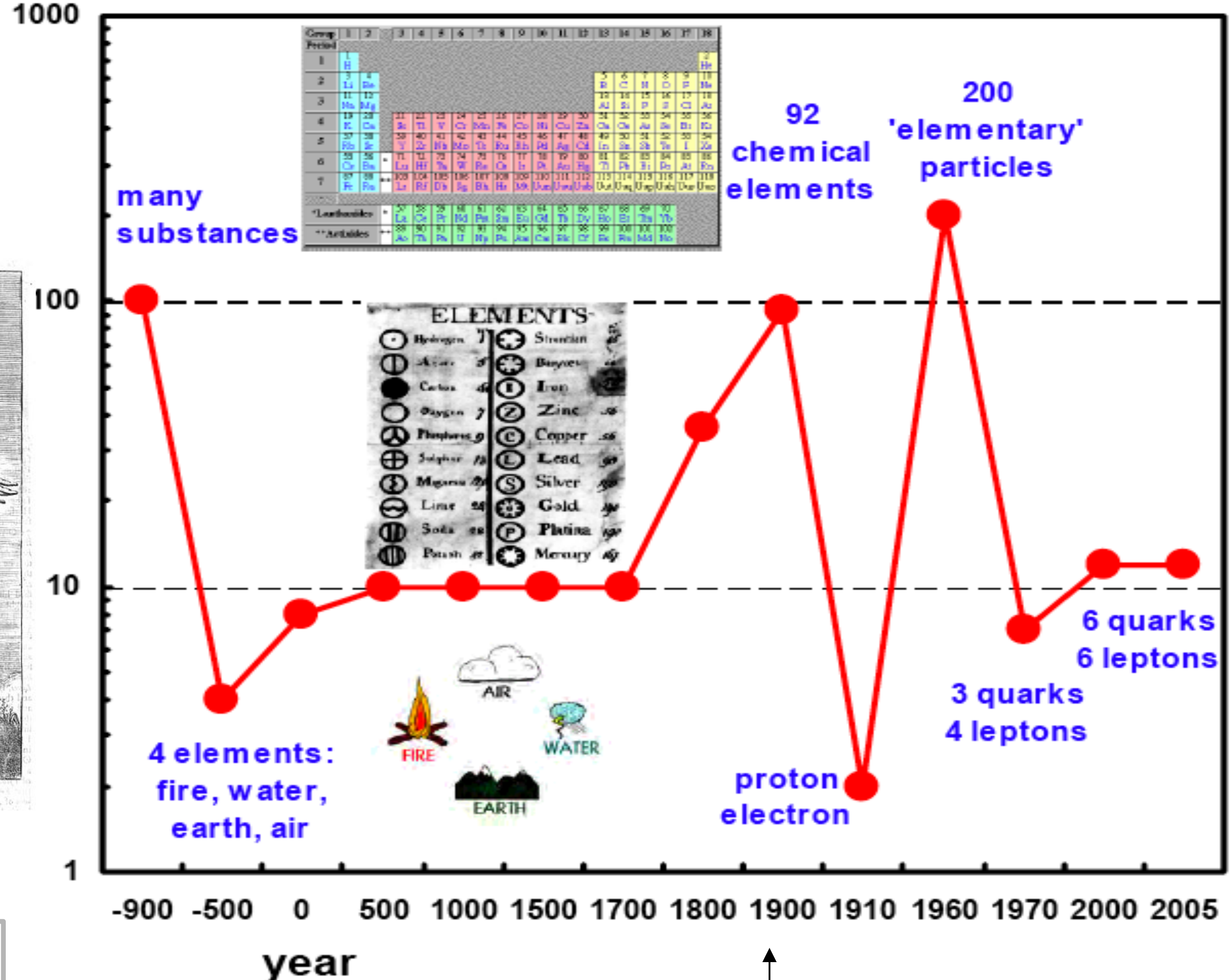
Higgs (2012) – the mass of elementary particles

… higher symmetries, extra dimensions, deeper structure..??

*) in 30 minutes for a personal selection of major steps in 100 years

From Empedoclez to today

490-430 BC, Sicily



Four elements and two forces (love and strife)

Lord Kelvin: “There is nothing new to be discovered in physics. All that remains is more and more precise measurement.”

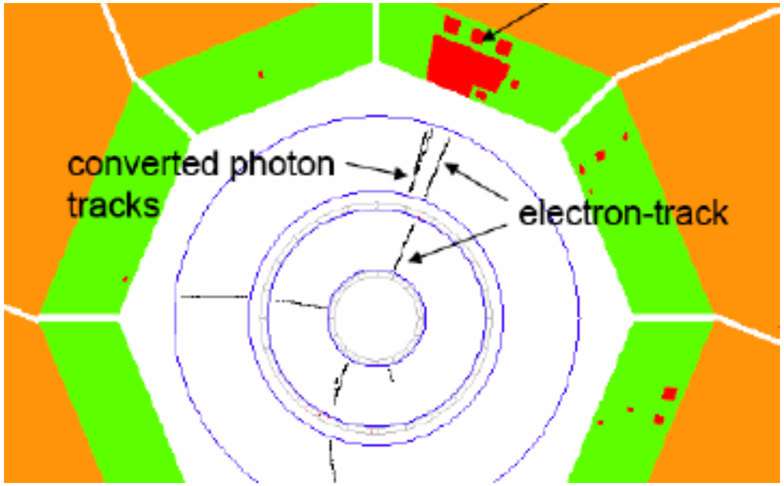
Electron e^-

Discovered: 1897 J.J.Thomson
[e/M
evacuated cathode ray tube
with external electric field and
fluorescent glass detector]

M=0.511 MeV, lightest lepton
spin 1/2 (Fermion), Q = -1
smallest charge: $-1.6\ 10^{-16}$ C

J.Thompson: Cavendish chair when 28. Particle hypothesis was supported by atomistic philosophy (linking back to Newton, Dalton) in England. In Germany, W.Kaufmann published the same observation, but an atomistic conclusion stood against Mach's ruling philosophy. "It is harder to crack a prejudice than an atom" Einstein cf Giudice

Electrons and photons in modern collider detectors (H1)

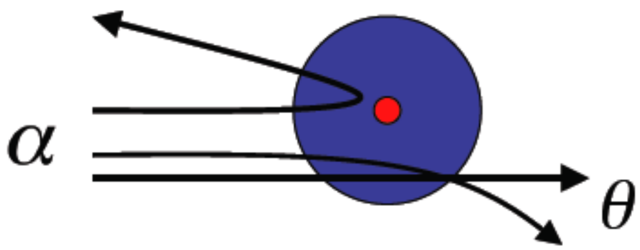


An electron is produced in ep. It radiates a photon, which converts into an e^+e^- pair. The three final state electrons deposit the energy in the heavy material of the "electromagnetic" calorimeter by further electromagnetic interactions (cf detector lecture to come)

Photon: discovered by Compton in 1923: M=0, Spin=1 (Boson), Q=0

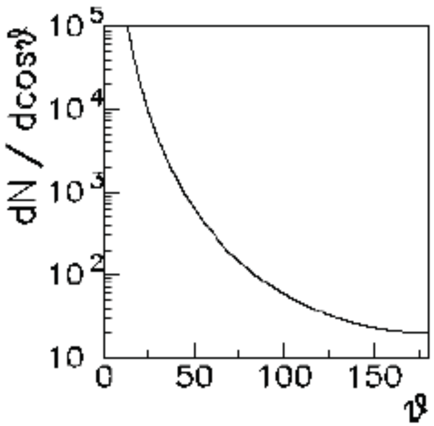
Atomic Nucleus and the Proton

Discovery of the atomic nucleus 1909



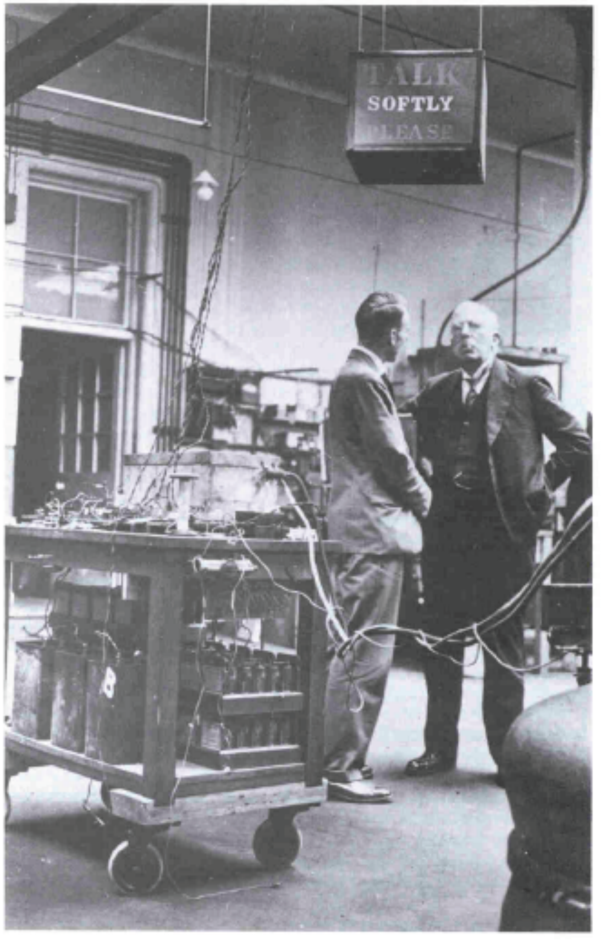
positively charged massive atomic nucleus

$$r_{nucleus} \approx r_{atom}/10000 \approx 10^{-14}\,\mathrm{m}$$



$$\frac{dN}{d\Omega} \propto \frac{Z^2}{E^2}\frac{1}{4\sin^4\theta/2}$$

$$E_\alpha = 5.5\mathrm{MeV}$$



Ernest Rutherford (1871-1937)

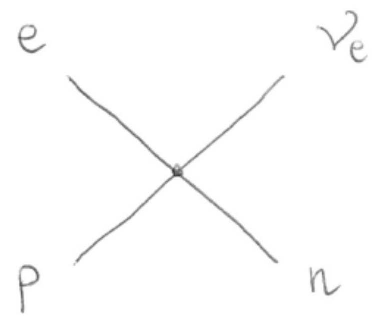
H. Geiger und E. Marsden

Proton discovery (1919) $\quad {}^{14}_{7}\mathrm{N} + {}^{4}_{2}\alpha \rightarrow {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{p}$

β-Decay and the Neutrino

e^- – emission n →p e^- ν
e^+ - emission p →n e^+ ν
K capture e p →n ν

Bohr, Heisenberg, Pauli…

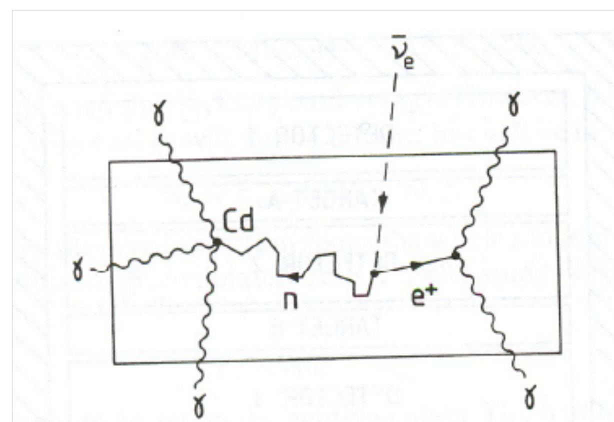


$$T = G_F(\bar{n}\gamma_\mu p)\cdot(\bar{\nu}\gamma_\mu e)$$

"4-Fermion Theory of β Decay"

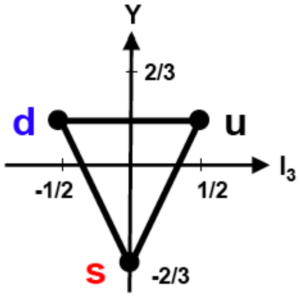
e -1897, μ -1936, ν_e – 1956, ν_μ- 1962
by 1962 we had four leptons
and a plethora of hadrons (p,n,K,π,..)

Fred Reines, Clyde Cowan
Savannah River Reactor
νp→ne^+ 1956



Double photon coincidence

Strangeness and the "inflation of hadrons"



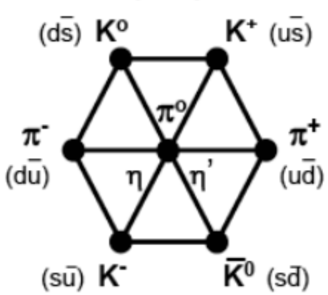
Quark

$Y = B + S$

$I_3 = Q - Y/2$

$J^P = 0^-$

$(\uparrow\downarrow)$



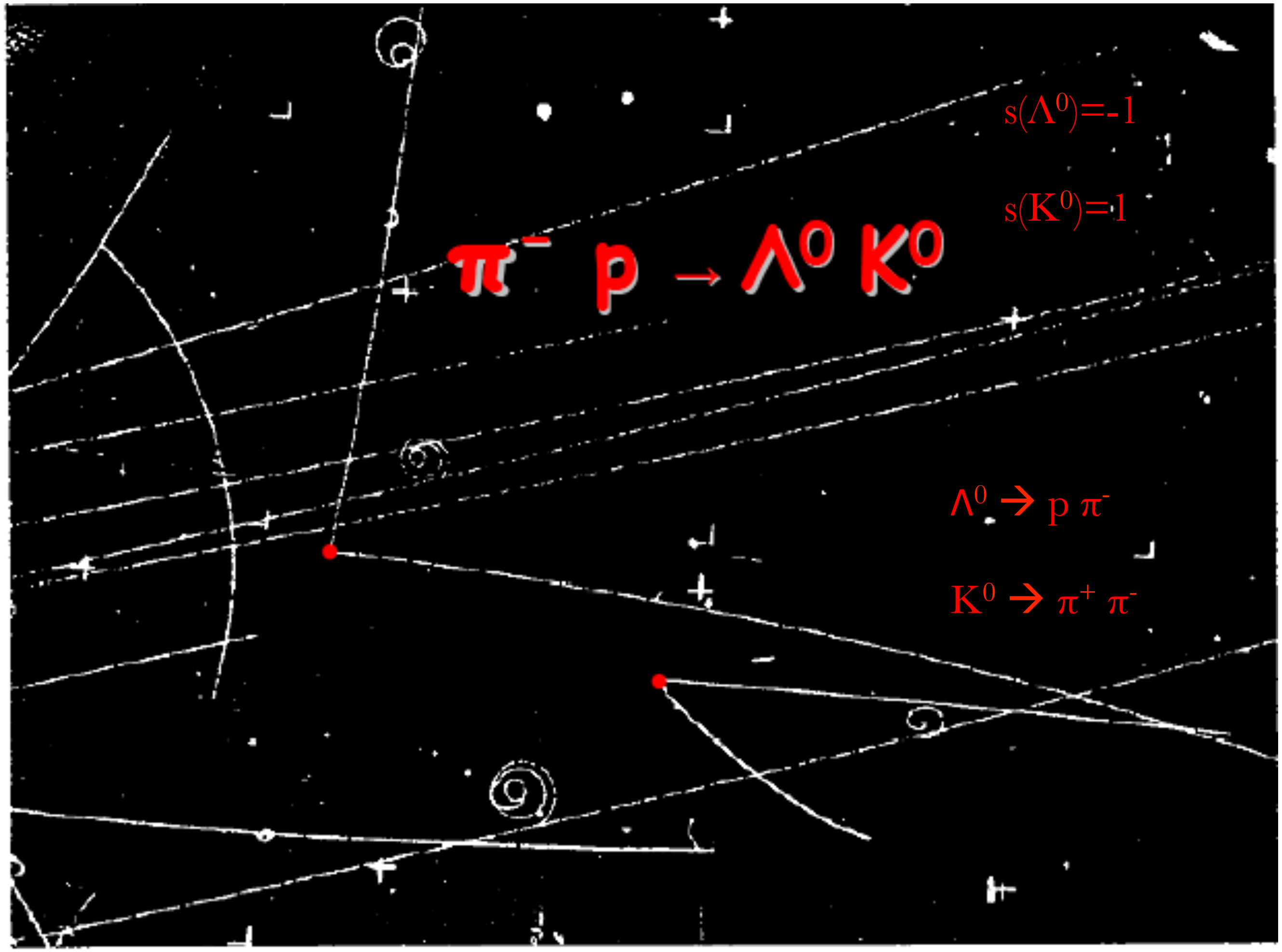


Fig. 12. Associated production, $\pi^- + p \rightarrow \Lambda^0 + K^0$ at about 1 GeV with subsequent decays in Alvarez's hydrogen bubble chamber.

Mesons, Baryons

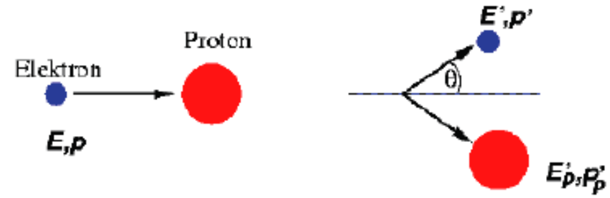
p=uud, n=ddu, Λ=uds..

Gell-Mann, Zweig (Quarks for the classification of hadrons)

Finite Proton Radius

Tuesday Afternoon: Accelerator Physics, R. F. Bacher presiding.

Hofstadter opened the discussion with a presentation of some of the extremely elegant electron-scattering work being done by a large group consisting of himself and J. Fregeau, B. Hahn, R. Helm, A. Knudsen, R. McAllister, and J. McIntyre.



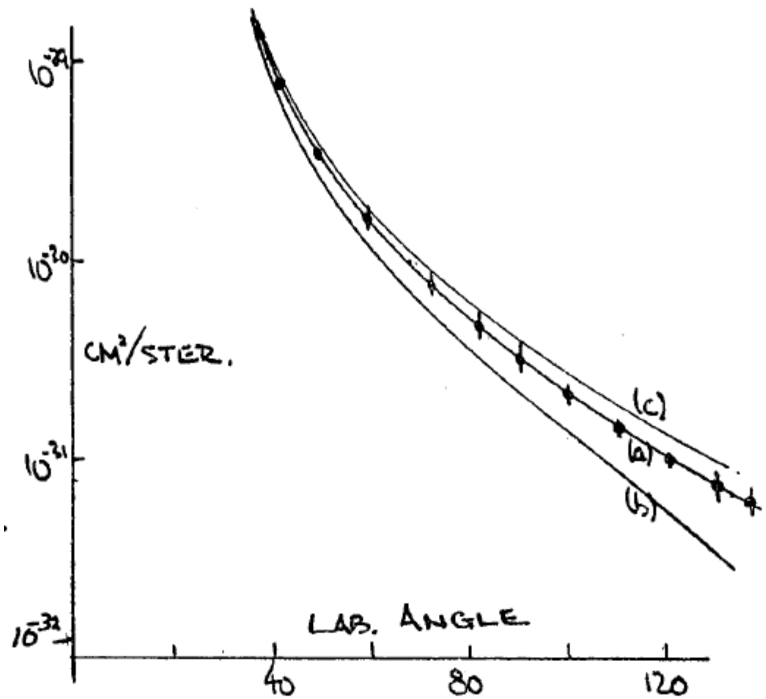


Fig. 2

Rochester Conference 1955

Elastic ep → ep scattering

E_e=188 MeV

Formfactor: $f(Q^2)=1+Q^2/6 <r_p^2>$

$r_p=(0.74\pm0.24)$ fm

Q^2 = negative 4 momentum transfer squared

Note: E' calculable from conservation principles

Rutherford (1911), Geiger, Marsden (1909):
αAu scattering: $r_{nucleus}=10^{-4}$ Å = 10fm

Proton Excitations - Resonances

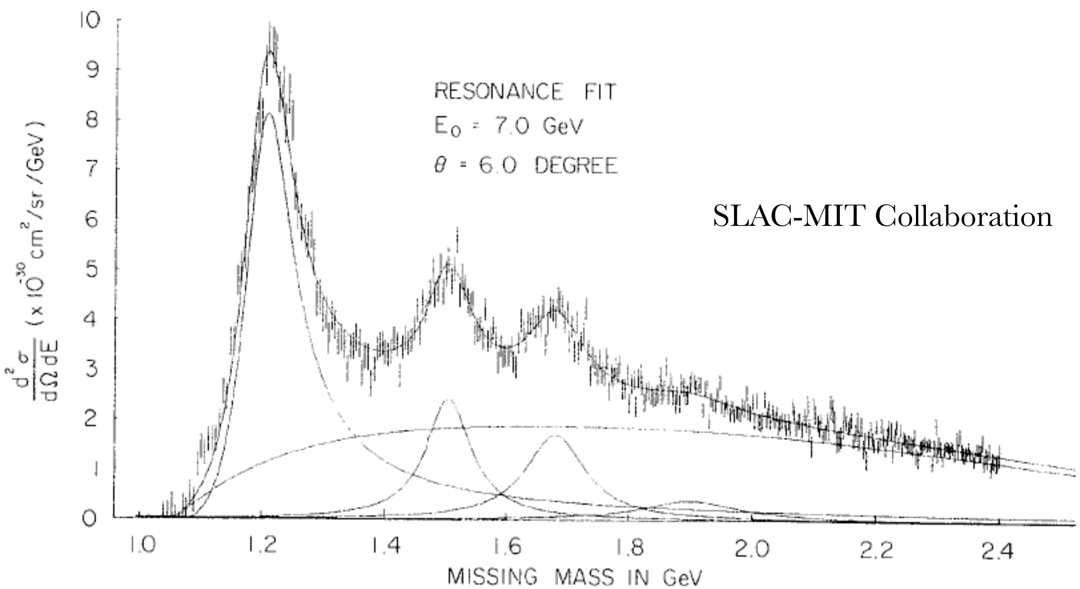


FIG. 5. Excitation spectrum of the proton as observed in the scattering of 7 GeV electrons through 6° (from SLAC-MIT Collaboration, 1968). The "missing mass" is the mass of the hadronic system, $\sqrt{(k+p-k')^2}$, where k and k' are the initial and final electron 4-momenta, and p the initial proton momentum (see §III.A.3, Vol II). The data have been fitted by four resonances, the most massive of which is barely discernable, and a smooth, nonresonant background. The three clearly visible resonances are Δ(1232), N(1520), and N(1680), in the notation defined in Table 1.

$$N=\left|\mathbf{I}=\tfrac{1}{2}\right\rangle\begin{cases} p=\left|\mathbf{I}=\tfrac{1}{2},\mathbf{I}_3=+\tfrac{1}{2}\right\rangle \\ n=\left|\mathbf{I}=\tfrac{1}{2},\mathbf{I}_3=-\tfrac{1}{2}\right\rangle \end{cases},\quad \Delta=\left|\mathbf{I}=\tfrac{3}{2}\right\rangle\begin{cases} \Delta^{++}=\left|\mathbf{I}=\tfrac{3}{2},\mathbf{I}_3=+\tfrac{3}{2}\right\rangle \\ \Delta^{+}=\left|\mathbf{I}=\tfrac{3}{2},\mathbf{I}_3=+\tfrac{1}{2}\right\rangle \\ \Delta^{0}=\left|\mathbf{I}=\tfrac{3}{2},\mathbf{I}_3=-\tfrac{1}{2}\right\rangle \\ \Delta^{-}=\left|\mathbf{I}=\tfrac{3}{2},\mathbf{I}_3=-\tfrac{3}{2}\right\rangle \end{cases}$$

Inelastic scattering: ep → eX

Production of excited states and, with higher energy, of new particles

Here: X=Δ (1.28 GeV)

Hadrons ("strong")

Baryons (p,n,Δ, …) – half integer spin
Fermions (π,K, ..) – integer spin

$Q=I_3 + Y/2$ [Gell-Man&Nishijima]

charge = isospin + hypercharge/2

Hypercharge: Y=B + s + c + b

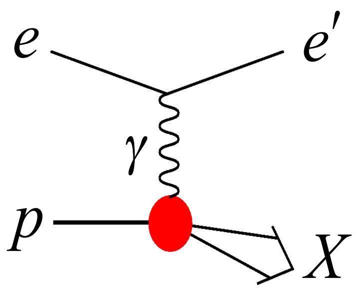
Proton: B=1, s=c=b=0: Q=1

Neutron: B=1, s=c=b=0: Q=0

Delta: B=1, Q=-1,0,1,2

Resonance formation, finite radius and magnetic moments hint to structure of nucleons …

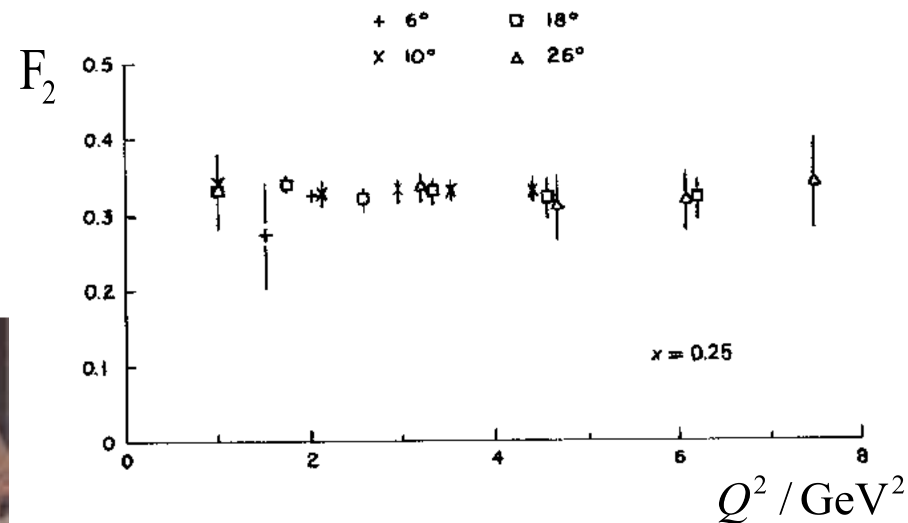
The discovery of partons in deep inelastic ep scattering in1969

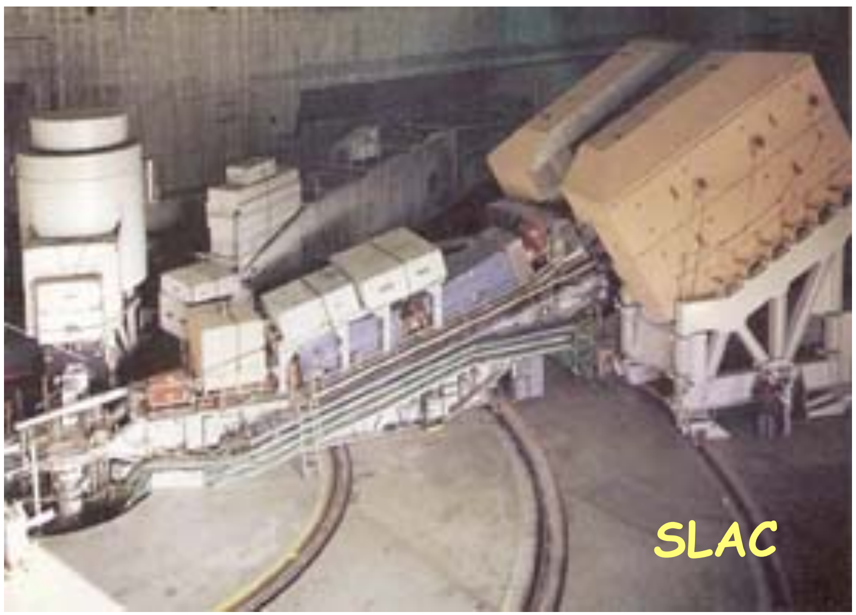


$$E_e = 1.5 \ldots 20\ \mathrm{GeV}$$

$$\theta = 6° \ldots 26°$$

$$Q^2 = 1 \ldots 7\ \mathrm{GeV}^2$$





Friedman, Kendall, Taylor (SLAC-MIT experiment)

Bjorken scaling as evidence for the existence of pointlike scattering centers inside proton

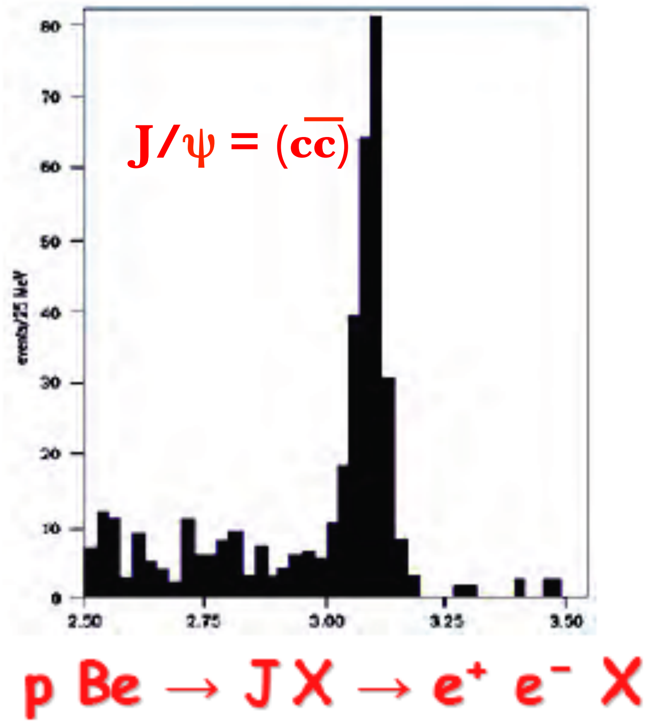
x = momentum fraction carried by quarks

Q^2 negative 4 momentum transfer squared

ν=E-E': energy transfer = energy of the photon

spatial resolution: $d = 1/\sqrt{Q^2} = 10^{-16}$m

The 4th Quark



Discovered 1974 by
Burt Richter et al., in $e^+ e^- \to \psi$ and
SamTing et al., in $pBe \to J\, X \to e^+ e^-\ X$
November Revolution M_c=1.5 GeV

Quark mixing introduced by Cabibbo in 1963 to explain the suppression of weak charged currents changing strangeness and generalised by Glashow, Iliopoulos and Maiani (1970) to explain the suppression of weak neutral currents changing strangeness

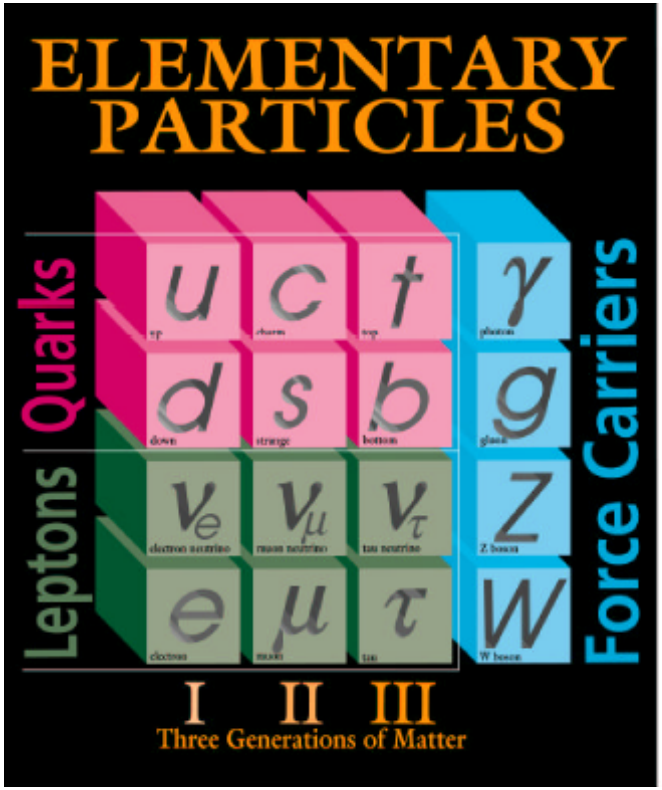
$$\begin{pmatrix} u \\ d' \end{pmatrix}, \begin{pmatrix} c \\ s' \end{pmatrix}$$

$$d' = d\cos\theta_c + s\sin\theta_c$$

$$s' = -d\sin\theta_c + s\cos\theta_c$$

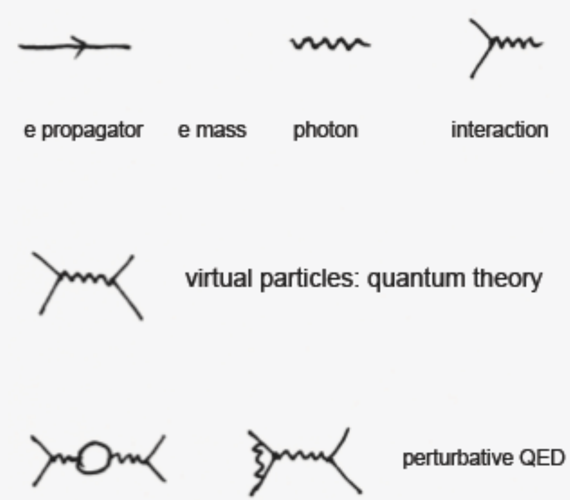
In 1974 l-q symmetry was thus restored.
Quarks had been regognised as elementary though confined particles.
The “Standard Model” was born in 1978 when the weak coupling structure of the Glashow, Weinberg Salam model had been confirmed (in an ingenuitive polarised ep scattering experiment by C.Prescott et al.)

Standard Model of Particle Physics [02/13]



Renormalisable gauge field theory of electromagnetic, strong and weak interactions.

$$L_{QED} = \bar{\Psi} D \Psi + m \bar{\Psi} \Psi + (DA)^2 + eA\bar{\Psi}\Psi$$



Selfinteractions in QCD : Gluon gives mass to baryonic matter.
Unitarity Conservation: Massive $W^{\pm}$ and Z damp steady rise of weak cross sections with energy.
Higgs mechanism: to damp divergence of WW cross section.
Higgs particle gives mass to W,Z. The only scalar in the SM - Lederman: H, the god(damn) particle.

Supersymmetry regularises Higgs mass and may explain dark matter pp → gg→ H → γγ or 4leptons or …

Higgs*)

From the ATLAS and CMS discovery papers 2012

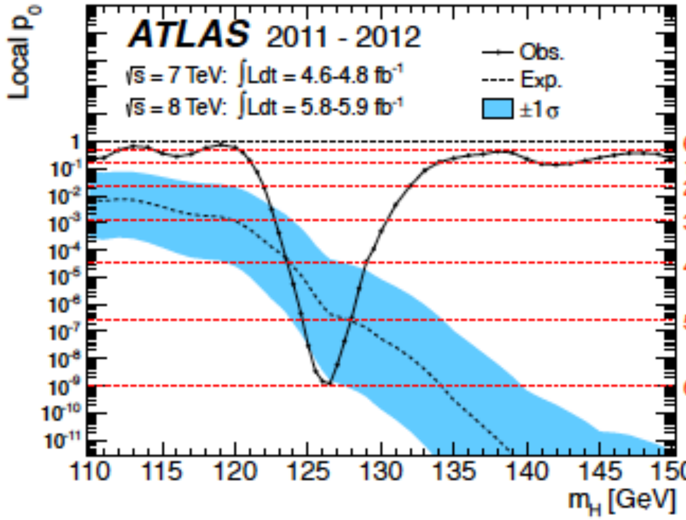
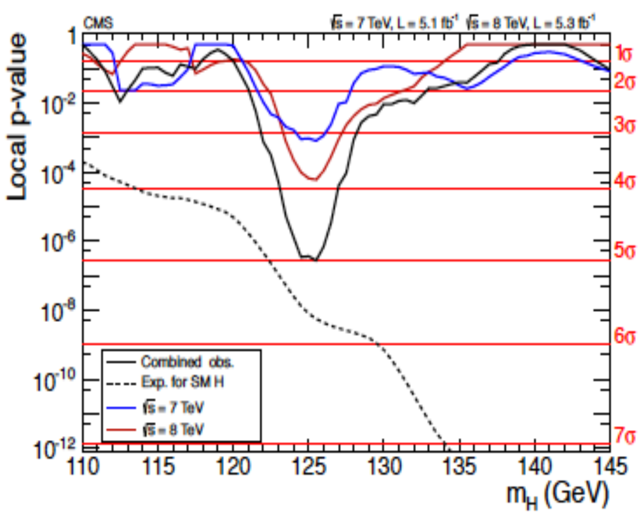


Figure 9: The observed (solid) local p_0 as a function of m_H in the low mass range. The dashed curve shows the expected local p_0 under the hypothesis of a SM Higgs boson signal at that mass with its $\pm1\sigma$ band. The horizontal dashed lines indicate the p-values corresponding to significances of 1 to 6 σ.



The photon is massless but the W and Z are massive. Their mass is explained in a "Φ^4" scalar field theory with its vacuum expectation value η of the potential $V=-\mu^2 \phi^+\phi - \lambda (\phi^+\phi)^2$, given by $\eta=\sqrt{(-\mu^2/2\lambda)}$. The Standard model mass relations are below, all parameters require(d) measurements from experiment (over 40 years..)

$$M_{W^+} = M_{W^-} = \frac{g\eta}{\sqrt{2}}$$

$$M_Z = \frac{M_W}{\cos\theta}$$

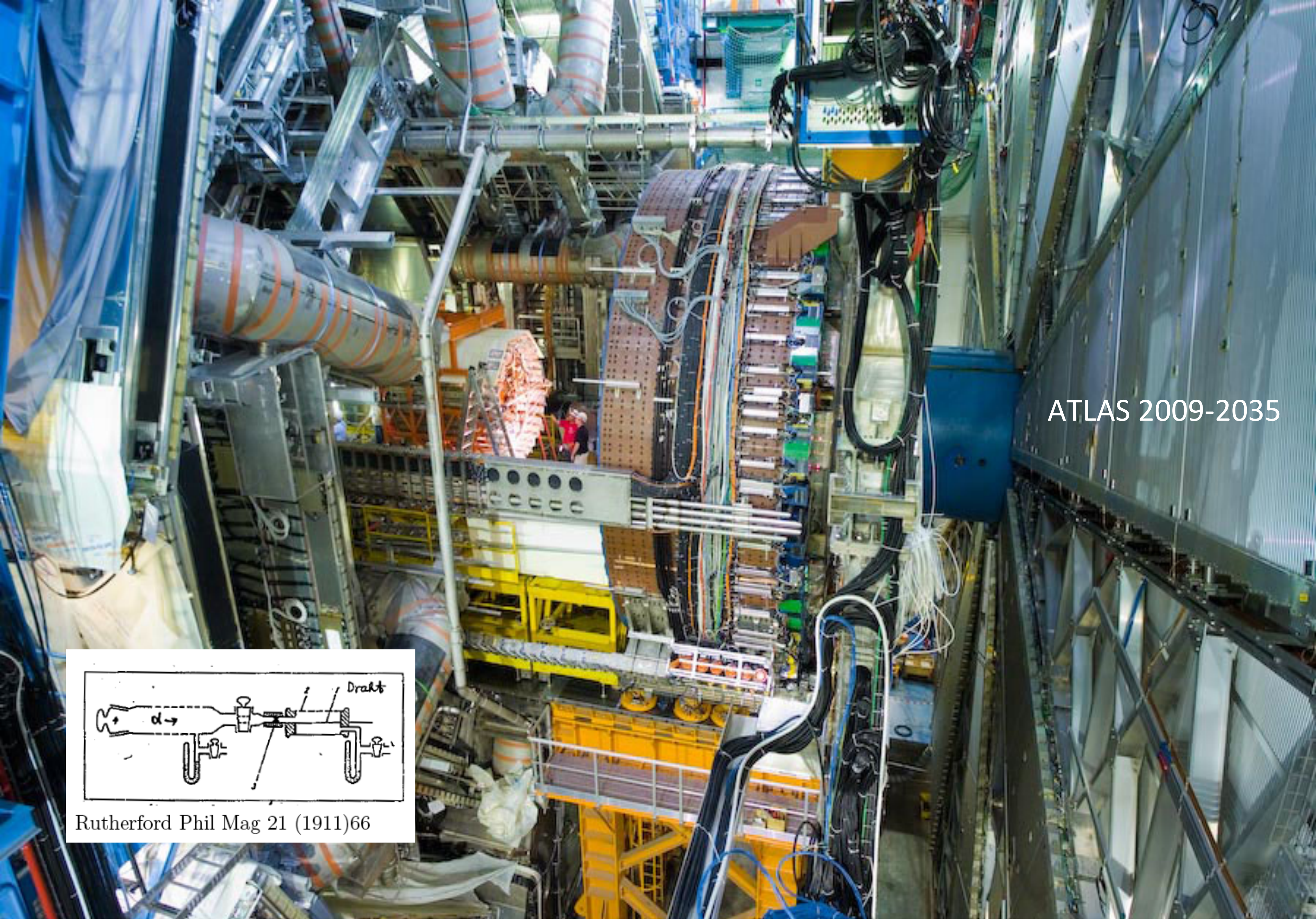
$$M_\gamma = 0$$

$$M_H = \sqrt{-2\mu^2} = 2\eta \cdot \sqrt{\lambda}$$

The W was discovered in 1984 at CERN and its mass of 81 GeV is now known to nearly 2 10^{-4}. Last year we have discovered a new boson in ATLAS and CMS at the LHC, which *likely* is the "Higgs particle" at a mass of about 125 GeV. W and H determine η and λ.

Note that g is the weak coupling constant, ~ Fermi's G

*) + Brout, Engler, Hagen, Kibble, Landau, …



Rutherford Phil Mag 21 (1911)66

Progress relied on the revolution of accelerators, instrumentation, electronics and computing over 100 years