Yet Another Introduction...

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Mass of Elementary Particles in the Standard Model

B.Sc Diploma Paper

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Mass and Energy

- A simple question: what is mass?
- Two concepts: inertial and Newtonian mass
- Einstein's General Relativity: Principle of equivalence

Symmetries in Physics

- Symmetries lead to conservation laws
- In classical mechanics:
  1) Uniformity of time -> energy conservation
  2) Homogeneity of space -> momentum conservation

- In classical field theory: theorem of Emi Noether
- Continuous transformations -> conservation of currents

- Global symmetry $\psi' = e^{i\epsilon}\psi, \bar{\psi}' = e^{-i\epsilon}\bar{\psi}$
- Example: the Dirac field $L = \bar{\psi}(i\gamma^{\mu}\partial_{\mu} - m)\psi$
- The conserved current $j_{\mu} = e\bar{\psi}\gamma_{\mu}\psi$

Local Symmetries

- Inner transformations
- Local symmetry $\psi' = e^{i\epsilon(x)}\psi, \bar{\psi}' = e^{-i\epsilon(x)}\bar{\psi}$
- We consider the Dirac field again
- To preserve the invariance of the Lagrangian, one can introduce the covariant derivative

$$D_\mu = \partial_\mu - ieA_\mu$$

- Now, the field obtains one more term

$$A_\mu' = A_\mu + \frac{1}{e}\partial_\mu \epsilon(x)$$

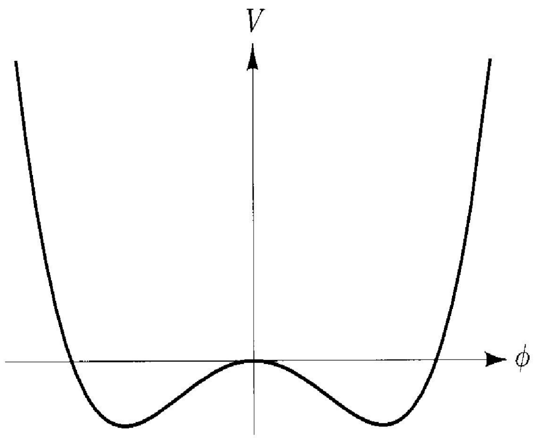
- Result: coupling with the gauge field (*i.e.* photon field)

$$L = \bar{\psi}[i\gamma^\mu(\partial_\mu - ieA_\mu) - m]\psi = \bar{\psi}(i\gamma^\mu\partial_\mu - m)\psi + e\bar{\psi}\gamma^\mu\psi A_\mu$$

Higgs Mechanism

- The same principle: fields of the matter couple to the Higgs field
- Spontaneous symmetry breaking – the system can choose between ground states

$$V(\phi) = -\frac{1}{2}\mu^2\phi^2 + \frac{\lambda}{4!}\phi^4$$



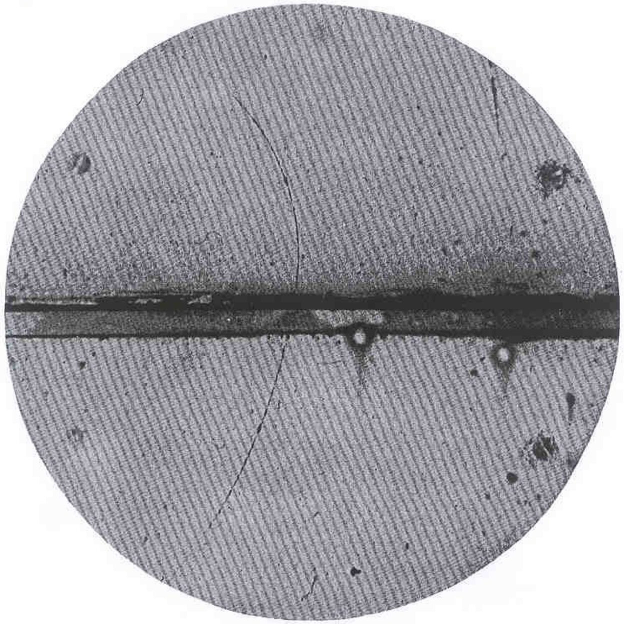
Standard Model

- Mass scale in the standard model
- Electron at rest has 510,998 eV = 511 keV
- Proton at rest has 938.272,013 eV = 938 MeV
- Top quark has 173,000.000,000 eV = 173 GeV

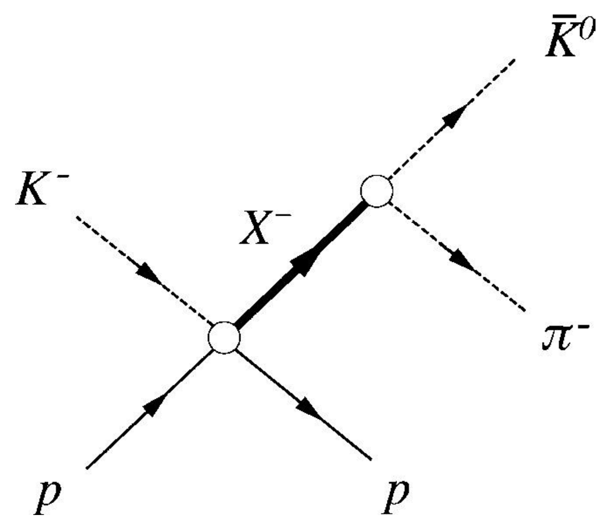
- For a comparison:
- Ionization energy for the H atom is 13.9 eV
- A molecule of a gas at room temperature has energy of 10^{-2} eV

Determining Mass Experimentally

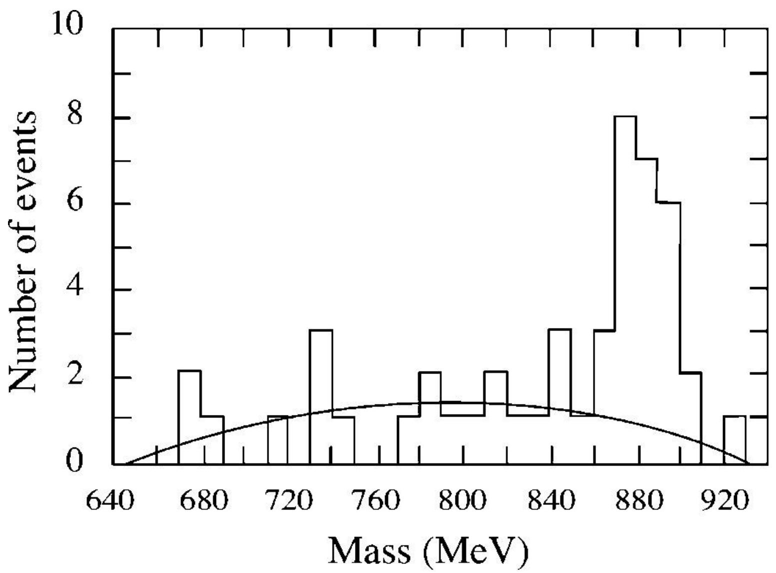
- The experiment that led to the discovery of positron (1932) and determination of its mass



Breit-Wigner Formula



- Example: determining the mass of a resonance
- Results from Alston *et al., Phys. Rev. Lett. 6, 520,* 1961. Experiment of $K^-\pi$ interactions at Lawrence Berkley National Laboratory



- The invariant mass is given by

$$W^2 = (E_K + E_\pi)^2 - (\vec{p}_K + \vec{p}_\pi)^2 = E^2 - p^2 = M^2$$

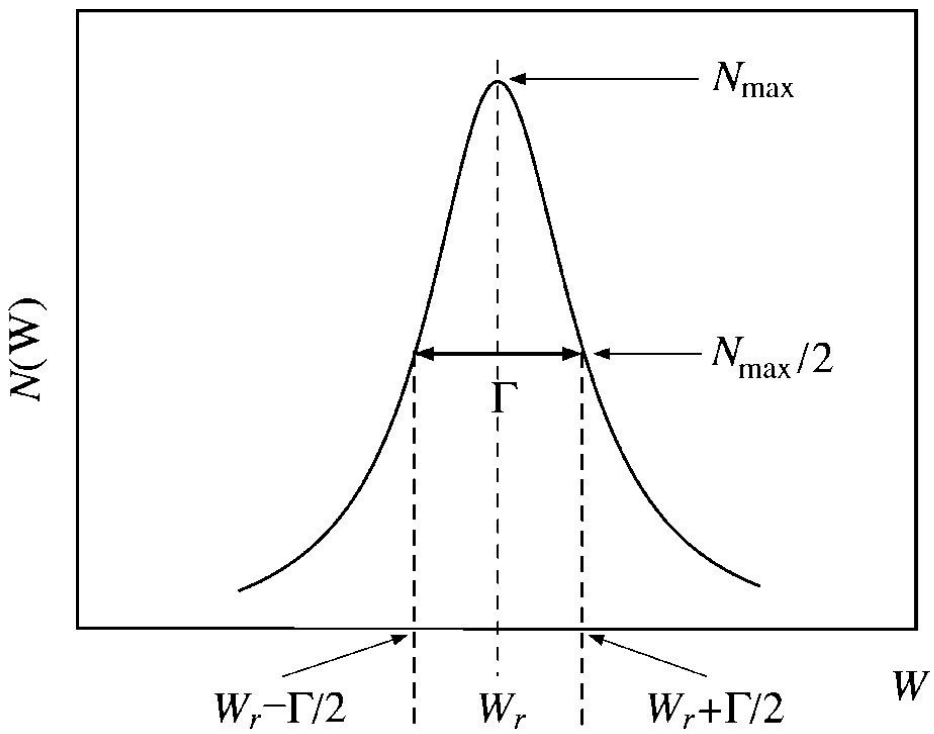
  - If this holds, then one will observe a narrow peak in mass distribution plot at M
  - The number of events in this experiment was 47, so even with poor statistics, the peak is observable

Breit-Wigner Formula

- The shape of the distribution is well approximated by Breit-Wigner formula:

$$W(N) = \frac{K}{(W - W_r)^2 - \frac{\Gamma^2}{4}}$$

- In case of one particle, W_r can be identified with its mass M



Summary

Table of masses (MeV)

Neutrino	<0.5 x 10^{-6}
Electron	0.511
u quark	1.7-3.1
d quark	4.1-5.7
s quark	100
Muon	106
c quark	1,290
Tau lepton	1,777
b quark	4,190
W-bosons	80,399
Z-boson	91,188
Higgs boson	>114,000
t quark	172,900