Experimental Evidence for the Standard Model

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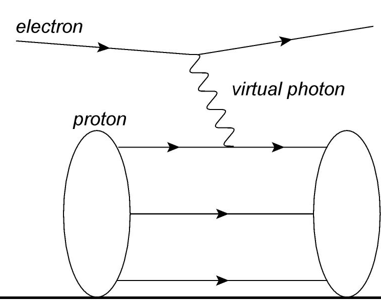
- Proposed the theory of quarks
- Predicted the existence and mass of a new particle, Ω^-
- The subsequent discovery at Brookhaven National Laboratory lent major support to the idea of quarks

Direct Evidence for Quarks

- 1960s
- Deep inelastic scattering experiments performed mainly at SLAC (Stanford Linear Accelerator)
  - Large energy transfer of a lepton on a hadron (deep)
  - After the collision, new hadrons are produced (inelastic)

- High energy particles with small wavelengths (leptons, usually electrons) are directed at hadrons to “see” what is inside
- The scattering of the leptons is consistent with the existence of very small, hard objects inside the proton



Conclusion 1

- There are three small constituent particles inside baryons and two inside mesons
  - evidence for quarks

- These experiments can measure the probability that a given constituent of the proton carries a fraction, *x*, of the proton's total momentum
  - Known as the structural function, $F_2(x)$
- The function peaks at x=0.3
  - This is consistent with the expectation that each of the three quarks inside the proton would carry (on average) one-third of the momentum of the proton

Conclusion 2

- These particles are charged, and their electric charge is either

$$\pm\frac{1}{3}e \quad \text{or} \quad \pm\frac{2}{3}e$$

  – Evidence for fractionally charged quarks

- The electron transfers energy and momentum to the proton through the exchanged virtual photon
- The interaction is electromagnetic and if the charge inside the proton was *e*, then the interaction strength should have an amplitude proportional to $\sqrt{\alpha_{EM}} \times \sqrt{\alpha_{EM}} = \alpha_{EM}$
- The amplitude is somewhat smaller, indicating a charge less than *e*
- Detailed measurements reveal the actual values of the charges

Conclusion 3

- The particles inside the hadron behave essentially as free particles, that is, they are loosely bound to each other
  - evidence for asymptotic freedom

- If the quarks were tightly bound to each other, a penetrating electron would deflect at a large angle
- The experiments show small defections indicating that the quarks rebound (a lot) when hit by the incoming electron
- This is only possible if the quarks are very loosely bound to each other inside the hadron

Conclusion 4

- Each of the constituent particles appears to come in three types
  - Evidence for color

- Let the amplitude of the Feynman diagram representing an electron scattering off a proton be *A*
- If color exists then three different Feynman diagrams are needed, each with amplitude, *A*
- The total amplitude of the process would be *3A*, in other words, larger
- Experiments show that the amplitude for the process is larger by the correct factor consistent with three colors

Conclusion 5

- There appear to be electrically neutral constituents inside hadrons
  - Evidence for gluons

- Because the interaction is electromagnetic, the electron can one “see” the charged constituents of the proton
- The momentum of the particles to which the electron couples can be measured
- The total momentum of these particles is less than that of the proton itself
- This means that there are other particles inside the proton that are electrically neutral
  - Taken for evidence of gluons

Asymptotic Freedom

- 1970s
- Realized that the interaction strengths are not constant
- The strengths depend on the energy that is transferred at the interaction vertices of a Feynman diagram

- 2004 Nobel prize: Hugh Politzer, David Gross, and Frank Wilzcek
- The strong interaction strength, α_{EM}, actually decreased as the energy increased
  - Known as asymptotic freedom
  - As the energy exchanged between quarks increases, the quarks behave as free particles rather than as tightly bound objects
- This is a purely quantum phenomenon and cannot be explained in classical physics

Z^0 and Neutral Currents

- Late 1960s: S. Weinberg, S. Glashow, and A. Salam developed the electroweak theory
  - Electromagnetic and weak interactions can be unified into a single interaction (based on symmetry)
- However, calculations of Feynman diagrams using this theory always gave meaningless answers

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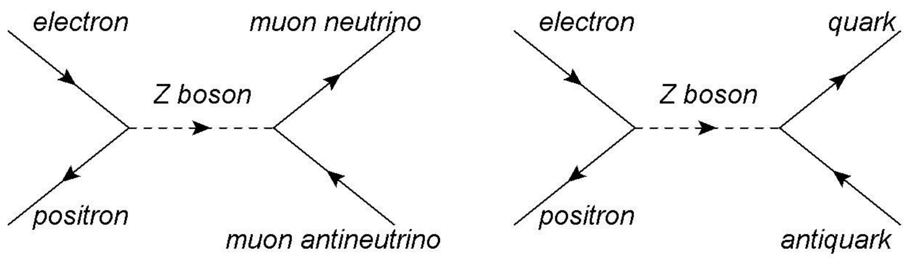
- 1970s: Gerardus 't Hooft and Martinus J. G. Veltman (Dutch)
- Showed that the infinite answers could be eliminated and that meaningful calculations could be done using the electroweak theory
- 1983: Z^0 particle was detected at CERN
  - Proton/antiproton beams at 270 GeV
  - Z^0 immediately decayed into electron-positron pair
  - Measurement of energy and momentum of the electron and positron allowed for calculation of mass of the original decaying particle, Z^0

- Only the standard model predicted neutral current processes
  - Technical name for processes mediated by a massive, neutral particle (Z^0)



- The discovery of Z^0 was therefore, the most convincing confirmation of the validity of the standard model
- $W^{\pm}$ were also discovered in the same experiments