Theories versus Experiments

Roger Barlow
The University of Huddersfield

LHC physics school, NCP Islamabd

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Summary

The usual model of progress in science (and particle physics in particular) is

1. Theorists make predictions
2. Experiment verifies these predictions
3. Repeat

and knowledge is constructed like a pyramid, each step acting as a foundation for the next layer

In reality things are not nearly so neat and ordered- though history re-writes events to fit the usual model

Why does it matter? Because the story isn't over.

Let's look at some examples

1932: The positron

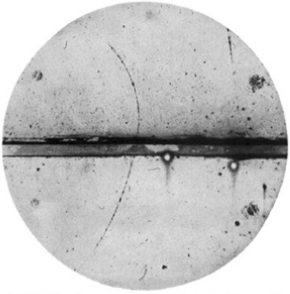
According to the textbooks

In 1928 Dirac predicted existence of the anti-electron or positron. It was discovered by Anderson in 1932

The very elegant Dirac equation

$$i\gamma^\mu \partial_\mu \psi(x,t) = m\psi(x,t)$$

requires that the γ^μ are 4x4 matrices and ψ is a 4-component vector describing solutions with negative energy, which behave like positively charged electrons



Anderson's positron: track going upwards (shown by loss of energy passing through plate) it curves to the left in the magnetic field, showing its charge is positive.

But...

- Other people had already seen such tracks, though not so clearly: Chao, Skobeltsyn, the Joliot-Curies...
- Anderson was unaware of Dirac's work
- Dirac's 1928 paper does not 'predict the positron'. It refers to the negative energy solutions as a possible problem. He later suggested they might be protons.
- Blackett and Occhialini had much better photographs, but delayed publication through caution
- Blackett and Dirac had met and talked, but did not make the connection

The real story (?)

The 1928 Dirac equation predicts positrons, and Anderson discovered one in 1932. But there is no clear causal link between them

1932: The neutron

According to the textbooks

Also in 1932, Chadwick produced a new, very penetrating, form of radiation by bombarding beryllium with α particles. He called this new particle the neutron

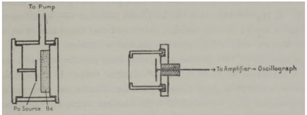


Fig. 1.

J Chadwick,
Proc Roy Soc **136** p 692 (1932)

He was not the first! It had been seen by Bothe, Webster, and the Joliot-Curies.
They all assumed it was gamma rays
Chadwick looked at the signals produced by the recoils, and showed they were characteristic of collisions with heavy ($m \approx m_p$) particles, not from photons.

Why...

He looked for this because he was looking for the neutron. He had a theory (suggested by Rutherford)

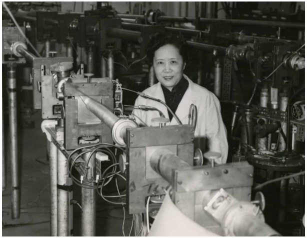
or adopt another hypothesis about the nature of the radiation. If we suppose that the radiation is not a quantum radiation, but consists of particles of mass very nearly equal to that of the proton, all the difficulties connected with the collisions disappear, both with regard to their frequency and to the energy transfer to different masses. In order to explain the great penetrating power of the radiation we must further assume that the particle has no net charge. We may suppose it to consist of a proton and an electron in close combination, the "neutron" discussed by Rutherford* in his Bakerian Lecture of 1920.

When such neutrons pass through matter they suffer occasionally close

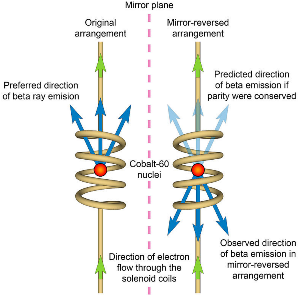
* Rutherford, 'Proc. Roy. Soc.,' A, vol. 97, p. 374 (1920). Experiments to detect the formation of neutrons in a hydrogen discharge tube were made by J. L. Glasson, 'Phil. Mag.,' vol. 42, p. 596 (1921), and by J. K. Roberts, 'Proc. Roy. Soc.,' A, vol. 102, p. 72 (1922). Since 1920 many experiments in search of these neutrons have been made in this laboratory.

His 'neutron' was a proton-electron combination. Not an elementary particle in its own right. He explicitly says 'this view has little to recommend it at present'.

1957: Parity Violation



At the suggestion of Lee and Yang, Wu measured the direction of electrons emitted in the β decay of polarised Co^{60}, and showed they tend to come out along the field direction



Solves an old puzzle

This gives us a way of defining ‘left’ and ‘right’ in absolute terms - a problem that goes back to Immanuel Kant

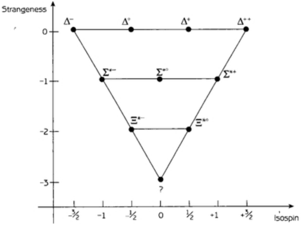
And then suddenly

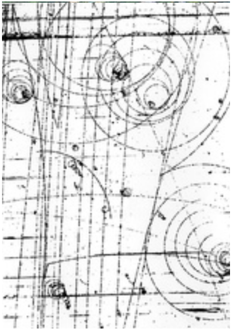
Nobody had bothered to measure this, because parity (mirror symmetry) was a fundamental belief. The result made many theorists (Pauli, Landau...) very unhappy.

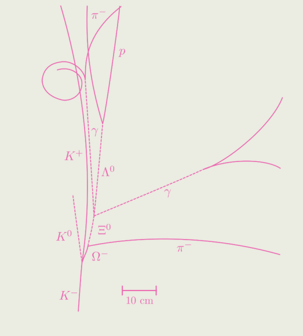
After this result, a flood of others followed showing parity-breaking in the weak interaction (forward-backward asymmetry in muon decays, circular polarisation of gamma rays, longitudinal polarisation of β particles...) including previously ignored results.

1964: The discovery of the Ω^-

Gell-Mann suggested that 9 known hadronic resonances (Δ, Σ^*, Ξ^*) were an incomplete decuplet, predicting the existence and mass of an S=-3 called Ω^-







Discovered in a dedicated K^- run at the Brookhaven bubble chamber.

Theory predicts, so experiment verifies

But even so

The theory was not the quark model

Physics Today 17, 4, 57 (1964); https://doi.org/10.1063/1.3051535

ABSTRACT

A theory for strongly interacting particles has been given strong support by an experiment resulting in the discovery of a new particle whose properties had been accurately predicted by the theory. The new particle, the omega minus, is a hyperon of mass 1686 ± 12 MeV /c^2, charge −1, and is the only known particle with strangeness −3. The experiment, reported in the February 24 issue of *Physical Review Letters*, was done with the Brookhaven Alternating Gradient Synchrotron and eighty-inch bubble chamber, by a team of thirty-three physicists, headed by Ralph Shutt, with Nicholas P. Samios in direct charge of the experiment. The theory, independently developed by Murray Gell-Mann of California Institute of Technology and Yuval Ne'eman of Tel Aviv University, is known as the eightfold way because it requires the conservation of eight quantities.

It was 'The Eightfold Way': now generally referred to as 'accidental approximate flavor SU_3'

Incidentally, the Ω^- had been occasionally seen in previous experiments, but was not understood and ignored.

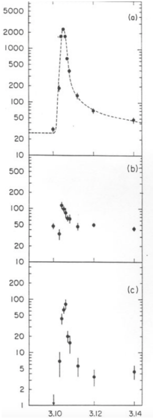
1974: The discovery of Charm

I was just starting the 3rd year of my PhD when the news broke

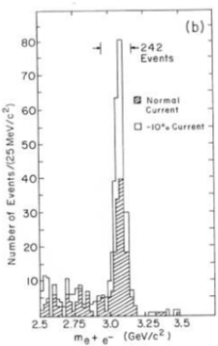
What the textbooks say...

Charm was predicted by Glashow, Iliopoulos and Maiani, and discovered by Richter at SLAC in e^+e^- annihilation and Ting at BNL in p-Be collisions

Richter saw a very narrow peak in the e^+e^- cross section



Ting saw a simlarly narrow peak in the effective mass of e^+e^- pairs



but it wasn't quite that smooth

Yes, but

1. Charm was only one of many predictions, and it was not mainstream
2. No-one suggested looking for it in narrow resonances, as we didn't understand the power of the OZI rule
3. Charmed particles (D mesons) had already been seen in a Japanese cosmic ray experiment, but ignored.
4. Identification of the J/ψ with charm was rapid but not immediately universal

From Richter's Nobel speech (1976)

To summarize briefly, the 4-quark model of the hadrons seemed to account in at least a qualitative fashion for all of the main experimental information that had been gathered about the psions, and by the early part of 1976 the consensus for charm had become quite strong. The $c\bar{c}$ system of charmonium had provided indirect but persuasive evidence for a fourth, charmed quark, but there remained one very obvious and critically important open question. The particles formed by the $c\bar{c}$ system are not in themselves charmed particles, since charm and anticharm cancel out to zero. But it is necessary to the theory that particles which exhibit charm exist ($c\bar{u}$, cd, etc.). What was needed, then, was simply the direct experimental observation of charmed particles, and the question was: Where were they [26]?

1979: discovery of the gluon

I was a postdoc on TASSO at the time

$e^+e^- \to q\bar{q}g \to 3jets$

The discovery of the gluon (continued)

What the physicists were thinking (according to the DESY website today)

To begin with, the accelerator was operated at low collision energies of around 13 gigaelectronvolts (GeV). This level was first increased to 17, and in the spring of 1979 to 27 GeV. Full of anticipation, the experimenters scanned the first data they had collected and were able to confirm some of the predictions made by the quark model. However, the search for the gluon was at the back of everyone's minds right from the start. Indirect hints for the existence of these adhesive particles had alrea

What they were really thinking (according to the PETRA bulletin, 1978). This refers to Mark J but the other experiments were similar.

The physics objectives are:

1. to measure the interference effect between the weak and electromagnetic interaction by studying the charge asymmetry in the reaction $e^+e^- \to \mu^+\mu^-$,

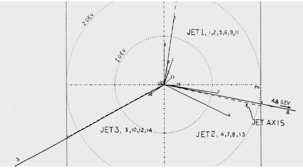
2. to measure the cross-section $e^+e^- \to$ hadrons,

3. to search for new heavy leptons and vector mesons,

4. to study the various quantum electrodynamic processes.

The discovery of the gluon (continued)

A few random hadrons can often fall into 3 clusters



First gluon event presented by Bjorn Wiik at the Bergen conference

TASSO went public thanks to

- Good luck
- Detector and software working well
- Brass neck
- Being sure it was there
- Knowing exactly what to look for

The last 2 points were due to the theory

Nuclear Physics B111 (1976) 253–271

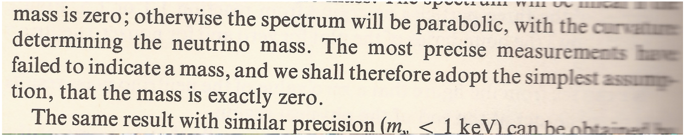
SEARCH FOR GLUONS IN e^+e^- ANNIHILATION

John ELLIS, Mary K. GAILLARD * and Graham G. ROSS
CERN, Geneva

Received 20 May 1976

1998: Neutrino Masses

m_ν is certainly very small, and was generally assumed to be zero.



mass is zero; otherwise the spectrum will be parabolic, with the curvature determining the neutrino mass. The most precise measurements have failed to indicate a mass, and we shall therefore adopt the simplest assumption, that the mass is exactly zero.

The same result with similar precision ($m_\nu < 1$ keV) can be obtained

R Omnes: "Introduction to Particle Physics", 1970

Davis wanted to detect neutrinos from the sun, a mile underground using 100,000 gallons of cleaning fluid (perchlorethylene: $C_2 Cl_4$) through

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{A} + e^-$$

${}^{37}\mathrm{A}$ is unstable. Periodically flush the tanks with helium and count decays.

Davis saw decays, but only at 1/3 of the rate predicted. (10 atoms/week)

This was known but ignored for decades:

- Some people didn't believe the experiment
- Some people didn't believe the theory
- Nobody appreciated what it meant

Neutrino Mixing

Davis continued to take data and the result refused to go away until

1. Other experiments (SAGE and GALLEX), which use lower-energy neutrinos, also saw a deficit
2. Kamiokande and SuperK (originally built to measure proton decay) saw deficits from atmospheric neutrinos.
3. SNO confirmed Davis but also measured elastic scatters which showed the total number of neutrinos agreed with the solar model

Neutrinos oscillate

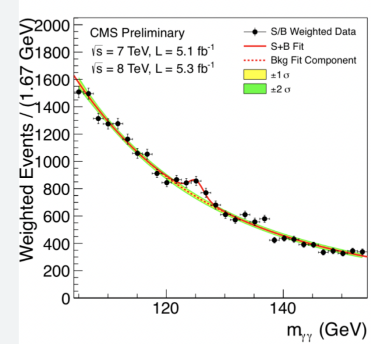
ν_e, ν_μ, ν_τ oscillate between the 3 types as they travel. After a long distance, only 1/3 of the neutrinos that started are still 'electron neutrinos'

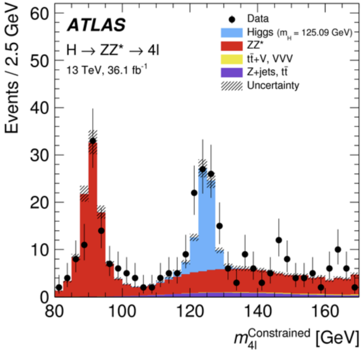
The oscillation happens because the wave function oscillates at 3 fundamental frequencies - $M_{\nu_{1,2,3}} c^2/\hbar$ - and they get out of step

As there are oscillations, neutrinos must have different masses - therefore they must have masses

2012: the Higgs

First seen in $H \to \gamma\gamma$, then also in other channels



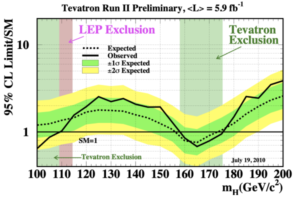


The final piece of the jigsaw

We already knew almost everything about it

And its mass had to be between 115 and 158 GeV

A triumph, but not a paradigm shift



Putting it all together

Discovery	Surprise level	Technology level	Pattern	Theory
positron	!	***	$E \leftarrow T$	Very new
neutron	!	**	$E \leftarrow T$	wrong
parity violation	!!!	**	$T \rightarrow E$	very unfashionable
Ω^-	-	**	$T \rightarrow E$	now superseded
charm	!!	**(*)	$E \leftarrow T$	niche
gluon	-	***	$T \rightarrow E$	Mainstream
m_ν	!!	***	$E \leftarrow T$	niche
Higgs	-	***	$T \rightarrow E$	Mainstream

Although some are of the traditional "Theory suggests: experiment verifies" pattern many are better described as "Experiment discovers, theory explains"

For these cases, early results are often ignored because they didn't fit the existing theory, or they weren't strong enough, or both

Conclusions

Theory predicts, Experiment confirms

Does happen, but it's only one pattern.
And for a mainstream theory the impact is small

Experiment discovers, theory (sooner or later) explains

Also occurs, though history tends to rewrite what happened as if it were all planned

A theory is essential

Without some theory, observations will be ignored.
We do need a theory - even if it's wrong

In today's and tomorrow's experiments, we must not be bound by mainstream theories. This is increasingly hard.

Good luck to all those who are, or will be, part of pushing back the boundaries