The False Discovery of the Top Quark

The Quark Model

INTRODUCTION

In physics, one tries to understand the nature and its complexity by looking at possible patterns that could be arranged in certain ways. Just like the chemical elements in the periodic table, in particle physics, accelerator technologies and the motivation of people themselves made it possible for physicists to understand even better the constituents of matter and classify them according to their properties, such as their quantum numbers.

So I'd like to take you a little bit back in time, in a fly by of the SM was being built piece by piece, starting in the early '60s when a fundamental model was introduced to serve this purpose, the Quark Model.

<u>The Eightfold Way</u>

In **1961**-1964 Murray Gell-Mann introduced the Eightfold Way. A simple way that arranged baryons and mesons into geometrical patterns according to their charge and strangeness. In this image you can see the baryon octet: eight lightest baryons fitting into a hexagonal array, with two particles at the centre. There's also the antibaryon octet, the baryon decuplet, meson octet etc. The Eightfold Way was a huge success and it was accepted as correct without a doubt. The importance of it was also in the organisational structure it provided, and one could say that it initiated the modern era in particle physics.

<u>The Quark Model</u>

The next question was to figure out why hadrons would fit into these patterns.

In **1964** Gell-Mann and George Zweig independently proposed that all hadrons are composed of even more elementary constituents which Gell-Mann called quarks.

This was the quark model. Most hadrons could be explained as composed of 2 quarks, up and down, and a strange quark for the strange mesons, was postulated at that time to explain the strangeness of the particles that were anomalously much longer-lived than the others.

In this image you can see the quarks forming a triangular "Eightfold Way" pattern. You would also have one for antiquarks.

The Quark Model explained the Eightfold Way even though they had to wait until the experimental evidence for the existence of the quarks.

This follows a period of skepticism in the late ‘60s and early ‘70s because the Quark Model couldn’t explain why the experiments were failing at producing and identifying individual quarks.

It wasn’t until 1968 at the Stanford Linear Accelerator (SLAC) centre where deep inelastic scatterings indicated that protons had a substructure, strongly supporting the quark model.

The experimentalists were colliding high-energy accelerated electrons with stationary protons, and measuring the angles at which the electrons came out from the collision. These showed that the proton acted as if it contained three lumps or hard point-like constituents, later called partons, exactly as it was expected in the quark model.

Then another theoretical objection to the quark model was that it seemed that it violated Pauli Exclusion Principle. To get out of this dilemma, Greenberg in 1964 suggested another quantum number for quarks, the colour, and this was known as the colour hypothesis. It explained that u-quarks in the Δ^{++} particle are no longer identical and this kind of “evaporated” the problem.

A parallelism between leptons and quarks arose further question about the existence of a fourth quark.

A fourth quark had already been predicted first by James Bjorken and Sheldon Glashow in 1964. In the image you see some of the possibilities of new baryons and mesons containing a fourth quark, the charm.

→ *In 1970, Glashow, Iliopoulos and Maiani provided more technical reasons for its existence.*

What put the quark model back to its feet was the discovery of the ψ meson (neutral, extremely heavy), as it already had an explanation for its extraordinarily long lifetime, $\tau \sim 10^{-20}$ s. It is a bound state of a new 4th quark and its antiquark, the charm.

First observation of it was in summer 1974 by C.C.Ting and his group in Brookhaven who named it J, and then independently discovered by another group at SLAC, published in November.

This followed with the first charmed baryons discovery in 1975 and first charmed mesons in 1976.

The image shows the first charmed baryon evidence in Brookhaven laboratory.

So the interpretation given by the quark model was no longer doubtful.

In 1975 the τ lepton was observed at SLAC (events with electrons and muons signaled the production of a new heavy lepton that could decay to electrons/muons and neutrinos) and later DESY confirmed it in 1978. This “spoiled” the symmetry as it introduced the third generation of elementary fermions. So 6 leptons and 4 quarks.

The image here shows a fixed-target area and spectrometer used in the SLAC experiment. And also Professor Perl who was working with his group at SLAC at that time.

In 1977 in proton-nucleus collisions E288 experiment at Fermi National Accelerator Laboratory (Fermilab), Leon Lederman and his team discovered the upsilon particle, a new heavy meson $\Upsilon = (b\bar{b})$. It was recognised as the carrier of the fifth quark, the beauty quark.

The image shows the whole group and Lederman and his colleague sitting.

Naturally, people were sure that another quark must exist and would soon be discovered. This motivated the searches for this isospin partner of the bottom quark to restore Glashow’s symmetry with six quarks and six leptons. (three generations, each with 2 quark pairs)

So the motivation was quite captivating and many early searches such as for a $t\bar{t}$ bound state - toponium - but they were unsuccessful because the electron-positron colliders did not reach high enough energy and because, which we now we realise as it is very short-lived and cannot form bound states - there are no top baryons and mesons.

The discovery of W and Z bosons

The EWK theory by Glashow, Weinberg and Salam had already provided a prediction and calculation of the existence of three intermediate vector bosons.

It was the discovery of the weak neutral currents by Gargamelle that caused the electroweak theory to be widely accepted. The Nobel Prize was awarded in 1979 to all three for the electroweak unification and the prediction of weak neutral interactions that implied the existence of the Z particle.

SPS and SppS

In 1976 CERN's Super Proton Synchrotron (SPS) started operating with a COM energy of $\sqrt{s} \sim 30$ GeV. But this was insufficient for the production of W and Z bosons.
"There is no doubt that Carlo Rubbia, with his enthusiasm, courage to strive for the impossible and charisma, played a key role in this phase of the project."

The same year, David Cline, Carlo Rubbia and Peter McIntyre proposed a modification of the SPS into a proton-antiproton collider. Proton and antiproton beams counter-rotating in the same beam pipe to collide head-on. This would yield COM energies in a range of 500-700 GeV, sufficient to produce the heavy W and Z particles. People have described Carlo Rubbia to have played a key role in this project, because despite many uncertainties, his enthusiasm, power of conviction and charisma was almost like an act of heroism.

A proposal for UA2 by Pierre Darriulat was made the same year and approved 2 years later. They both began operating in the same year, 1981.

In this image it's the SppS accelerator complex.

The PS proton beam at 26GeV was used on a fixed target to produce antiprotons at ~3.5GeV, creating about one antiproton per million incident protons. The antiprotons were stacked and stochastically cooled in the antiproton accumulator at 3.5GeV (Simon van der Meer played a significant role here). With a few times 10^{11} *antiprotons accumulated per day, the cooled antiprotons were re-injected into the PS, counter-rotating in the same beam pipe with a proton beam. Both beams are accelerated to 270GeV and brought into collision in two IP at* $\sqrt{s} = 540$ *GeV.*

January 1983, the discovery of W boson was announced by Carlo Rubbia's group. 5 months later the same team announced discovery of the Z along with the UA2 experiment. These discoveries led to a Nobel Prize for Carlo Rubbia and Simon van der Meer for his role in stochastic cooling in 1984.

In the image on the right we have a W boson event display by UA1 experiment in 1982. The pink arrow shows a high-transverse momentum electron, and soft particles in opposite direction to it. This is expected if an undetected neutrino balances the electron's transverse momentum.

On the left we have a Z boson event display by UA1 in 1983. The two white tracks reveal the Z decay into $e^{+}e^{-}$ pair that deposit their energy into the EM calorimeter.

This was huge news because it provided experimental confirmation of the electroweak theory in the SM of particle physics.

UA1 & UA2 detectors

At that time, there was a general incredulity in the particle physics community that UA1 could be built and even less operate in time, when compared with the much more focused design and modest size of UA2 detector.

But again this was possible largely thanks to Rubbia's absolutism or more diplomatically said, his unrelenting efforts, and to his great intellectual and professional capabilities that he showed.

UA1 was the first large-scale collaboration with around 130 physicists. It was huge, heavy and extremely complex, exceeding any other collider detector at that time. UA1 was designed as a more general-purpose detector compared to UA2.

UA2 was a smaller collaboration with around 50 physicists. It was optimised for the detection of $e^{\pm}$ pair from W and Z decays. It could explore a whole range of other physics, jets, neutral over charged energy ratio etc. It was ten times smaller with an emphasis on calorimetry. What is interesting about this detector is that tracking system operated without a magnetic field, which meant that it could measure the directions of charged particles but not their momenta because there was no curvature. So to compensate this limitation, the detector was surrounded by high-resolution calorimeters which were the key as they focused more on energy measurement to identify events with large energy deposits.

CERN shared the discovery with the world.

This picture shows the CERN announcement of the discovery in January 1983. Carlo Rubbia, Simon van der Meer, Herwig Schopper, Erwin Gabathuler, Pierre Darriulat from left to right.

Then Rubbia and Van der Meer celebrating their Nobel win.

UA1 paper 1984

So at that time events of the W decaying into electron and neutrino, or muon and neutrino had clean signatures, were well-understood and they paved the way to extend the search to novel decays such as semi-leptonic decays of the W.

Their event signatures were in agreement with the W decay to a top and a bottom quark.

The other (ud, or cs) were simply too difficult because of the relatively large QCD jet background.

There were some previous unsuccessful searches in e+e- colliders that set a mass limit above 22 GeV. Using the available energy from their hypothesis decay, they extended the search up to 65 GeV, so they inferred a mass for their hypothesis to be around 40 GeV. It was used for calculating the expected number of decays from the integrated luminosity for example.

There's a **systematic error** in the mass evaluation that comes due to uncertainties in the reconstruction of jets and the determination of the associated parton four-vectors.

When you do data analysis in particle physics, you want to keep as much signal as possible and at the same time remove as much background as possible in your dataset.

In their selection of events, they observed 12 events from each sample, the electron and the muon one.

From their number of estimated background events, to what they actually observed, this was a significant effect, corresponding to over 3SD.

What went wrong?

They had been underestimating their background, specifically the W decay channel to leptons and Terry Wyatt re-examined the analysis and argued that the tau mode for the W, which is followed by the leptonic decays of tau could accounted for the background processes.

So he found that the effect was not the result of some statistical fluctuation, but it was because of poor modelling of background because they didn't consider the tau channel.

It was said that he convinced them by challenging them with incisive questions about the analysis.

Why didn't UA1 include taus?

I think the reason might be because the electron and muon events are much cleaner (as they are stable particles and detectable, tau leptons don't leave a track in the detector because they decay so much quicker it can be observed) as they even state it on their paper. And it's easier for background estimation.

FAST FORWARD:

Searches for the top quark were done in the US, at Tevatron collider at Fermilab.

The top quark's existence was not fully established until 1995, when Tevatron finally accumulated enough data to sustain strong interactions. Fermilab was the only accelerator in the world capable of producing top quarks until LHC was built started to operate.

The official top quark discovery was announced by the CDF at Fermilab, then followed by D0 collaboration on the same year, with a slightly higher mass but it was found well consistent within the uncertainties.

The plot is from CDF results, showing the reconstructed event-by-event of the top mass.

Data is shown by the solid lines, and is compared to background shown by dotted lines, and the sum of the top quark pair signal plus background which is the dashed line.

You can also see the likelihood fit to extract the top mass from this distribution.

LESSONS:

Objectivity:

- People in large collaborations, with their reputations and possible fame can have their objectivity clouded from it. It can be difficult to make them see matters from a different way or even question/challenge them as they are convinced in their results and believe in their data.

Skepticism

- Always keep questioning your results and understanding what is telling you. Review and challenge your analysis, identify any possible aspect that might have been overlooked by mistake.

Scientific Discipline

- The strength of scientific method lies in the fact that it keeps evolving, refining and correcting as better understanding is gained with time. Just like the claim of

UA1 was quietly withdrawn as its flaws in the interpretation were finally revealed and understood.

Cross-checks with competitor experiments:

- results need to be reproducible, it's important to have other references, other experiments performing similar analyses and doing similar physics to confirm and reproduce your effects and results.

Complexity of experimental techniques:

- Modelling of physical processes, especially background modelling which is crucial for distinguishing a possible signal is very complex, and it requires good understanding of the physics processes and as good of tools to perform the analyses. A slight underestimation or missing key background information can lead to misinterpreted conclusions.

Under the physics you are dealing with:

- A better understanding of the physics will lead to better tools for exploring it.