The Third Generation:
From Conception to Adulthood

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An unusual event occurred in the world of physics: theoretical work led to a bold prediction for the existence of an important new meson with surprising properties. The approximate mass was calculated from theory and most other attributes of the new expected meson were also predicted. A new particle was discovered soon after, with properties which appeared to be consistent with the theoretical prediction. Anyone who knew about the prediction would have assumed that the newly discovered object is the meson wanted by the theory. But further experimental work showed that the new particle had additional puzzling properties, which did not fit the exact description of the original predicted particle. Then, a second totally new particle with approximately the same mass was discovered, to everybody's surprise. Confusion reigned for a while. Finally, it turned out that the first particle was totally unrelated to the theoretical prediction but the second particle was precisely the one predicted by the original theoretical analysis. The first particle just happened to be there, at the right mass range, and happened to have been discovered at the right time to cause total confusion. The first particle was not even a meson. It turned out to be a lepton. The second particle was the predicted meson. Until this very day we have no idea why nature produced a meson and a lepton, totally unrelated to each other, at the same mass range. The only possible explanation is that nature, like many of us, enjoys having fun at the expense of others.

From the late 1940s to the mid 1970s, the above story was familiar to every serious student of physics. It was the story of the discovery of the muon and the pion, following the brilliant prediction of Yukawa. But in 1975 history repeated itself in a remarkable way. The exact same story occurred again, forty years later, at a mass scale one order of magnitude larger, confusing physicists who were either young children or not yet born when the muon was discovered. In the first case, it took more than a decade to sort out the confusion. In the second case, it all happened in less than a year.

The following is my own personal version of the 1975 story. Most personal historical accounts rely on someone's memory, and the present story is no exception. But in presenting my version I have the extra luxury of using the same set of transparencies which I used, 17 years ago, in my Rapporteur Talk [1] to the 1975

Lepton-Photon Conference at Stanford (we refer to it as LP75). It was at that conference, that the confusion between the new lepton (τ) and the new charmed mesons (explicitly discovered only a year later) was first understood. It was a fascinating story, suitable for a detective novel. But, as we will see later, if someone would have written a story along the lines of the actual plot provided by the real world of science, no one would have believed it, published it, or made a movie out of it. It would have been rejected as being totally unrealistic.

In 1974, the world of particle physics consisted of four leptons and three quarks. There was no known reason for the existence of the muon and its own neutrino. There was no known reason for the existence of three quark flavors. But, given that there were four leptons and three quarks, there were good theoretical reasons to expect a fourth "charmed" quark. The original prediction of charm [2] was based on a superficial "why not?" argument. If there were three quark flavors, why not four? If there were four leptons, wouldn't it be nice to also have four quarks?

But a much more profound reason for a fourth quark came with the re-normalizable SU(2)XU(1) gauge theory of electromagnetic and weak interactions [3]. In this model, the absence of strangeness changing neutral currents [4], not seen by experiments, and the absence of a divergent contribution from triangle anomalies, not allowed by the theory [5], both required a fourth quark. A fourth quark, if it existed, would manifest itself in the form of new charmed mesons, expected at the mass range between 1.5 and 2 GeV, as well as new baryons and new mesons with "hidden charm."

There were also those who believed in the possibility that additional leptons existed. Here, the only argument was "why not?" No one ordered the muon but it did arrive. Perhaps another lepton, equally uninvited, would arrive, sooner or later. There was no good argument for expecting such a lepton at any specific given mass, but that should not have stopped anyone from looking for it.

This was the situation on the eve of the "November Revolution" of 1974, when the ψ particle was discovered [6] at SLAC and Brookhaven, opening a new era in particle physics. Within a few days after the discovery of the ψ, it became clear that the leading theoretical interpretation of the new discovery was the production of "hidden charm"; namely, the production of a meson consisting of a charmed quark and a charmed antiquark. The immediate prediction was that, at an energy slightly higher than the ψ mass, a new threshold should appear for the production of pairs of charmed mesons. The new threshold should manifest itself first and foremost as a step function in the total hadronic cross section for electron-positron collisions, but also in several other ways which could be noticed only when the hadronic events were analyzed in detail.

Most properties of the expected charmed mesons were clearly predicted by the theory, including their dominant decay into strange particles and their production in pairs both in hadron and in electron-positron collisions.

A clear increase in the hadronic e^+e^- cross section was indeed observed by the SLAC-LBL team in January 1975 [7] and it appeared that the discovery of charmed mesons was just a few weeks away. The detailed theoretical expectations were as follows (Figure 1):

(1)   On the basis of the masses of the ψ particles, it appeared that the mass of the lightest charmed meson should be around 2 GeV, leading to a new threshold around 4 GeV in $R_{e^+e^-}$. Such a clear threshold was observed.

(2)   Most charmed mesons must decay to strange particles. Consequently, the overall K/π ratio in the hadronic events must increase significantly above the new threshold. The data did not show any such effect.

(3)   The average total multiplicity for the decay of a charmed meson was expected to be around 4 with a charged multiplicity of 2.7 or so. Consequently, the total charged multiplicity of a typical event with a pair of charmed mesons was expected to be around 5.5, significantly larger than the average for normal hadronic events below the charmed meson threshold. That meant that as the energy increased above 4 GeV, one should have observed a clear rise in the average charged multiplicity of the hadronic events. No such increase was observed.

(4)   On the basis of the expected average multiplicity for charmed meson decays, the exclusive decay modes into $K\pi$ and $K\pi\pi$ should have been sufficiently frequent to enable us to see peaks in the invariant mass distributions of the observed events. No such peaks were observed. It was possible to explain the absence of such peaks by saying that the average multiplicity may have actually been larger than expected, rendering the low-multiplicity exclusive decays more rare. But in that case, the multiplicity increase mentioned above should have been even more pronounced (and this was clearly not the case). Conversely, if the failure to observe an increased multiplicity was due to charmed mesons decaying into smaller numbers of particles than expected, the $K\pi$ and $K\pi\pi$ peaks should have been even more prominent. In reality, neither peaks nor increased multiplicity were observed, creating what was called "the multiplicity crunch."

D - SPECTROSCOPY

① MASS ~ 2 BeV

THRESHOLD : $e^+e^- \to D\bar{D}$ (W = 4 BeV)

② MOST DECAYS INCLUDE K.

LARGE K/π RATIO.

③ $\langle n \rangle \sim 4$, $\langle n \rangle_{ch} \sim 2.7$

④ $\dfrac{E_{ch}}{E_{tot}}$ NORMAL, BUT "$\dfrac{E_{ch}}{E_{tot}}$" SMALLER.

⑤ INCLUSIVE $e^+e^- \to D\bar{D}$ ⤷ HAD. ⤷ HAD. ⟶ x < .5
↳ HAD.

⑥ $K^-\pi^+$, $K^-\pi^+\pi^+$, etc DECAYS.

⑦ SMALL $e\nu, \mu\nu$ DECAYS.

⑧ $R = 3\frac{1}{5}$ (+10−20%)

Figure 1: Expected properties of hadronic events above the new threshold at 4 GeV, based on the assumption that the step in R is due to pairs of charmed mesons. A transparency from LP75 [1].

(5) Charmed mesons were expected to decay rarely to $e\nu_e$ and $\mu\nu_\mu$. However, such events were observed in numbers far exceeding the expectations.

(6) The total e^+e^- hadronic cross section, normalized to the point-like cross section for $\mu^+\mu^-$, was predicted to be R = 3.3 above the charm threshold. This was the sum of the squared charges of the four flavors of quarks, counting three colors for each flavor. Between the experimental errors and the radiative corrections, there could have been an uncertainty of 10%–20%, allowing for a maximum R-value of perhaps 4. In reality, the step observed in the value of R was much larger. Above 4 GeV, the observed R-values were around 5.

There were additional predictions related to the ratio of charged to neutral energy and to the inclusive charged particle spectra, but they need not concern us here.

So, after the great relief and satisfaction when the actual step in R was clearly observed, everybody suspected that these were indeed events in which pairs of new particles were being produced (as expected for charmed mesons). But everything else was totally wrong: no enhancement of strange particles, no increased multiplicity, no $K\pi$ or $K\pi\pi$ peaks, too many $e\nu$ and $\mu\nu$ events and too large a value for R (Figures 2, 3).

Many of us at SLAC and elsewhere were sure that charmed mesons existed and that they were being produced in large numbers in the available data of the SLAC-LBL collaboration. But with every passing week, our frustration increased. We were looking for the "smoking gun" that would have convinced us that we were indeed observing pairs of charmed mesons. The gun could not be found. I remember long conversations with members of the SLAC-LBL collaboration and marathon discussions within the SLAC theory group, especially with Fred Gilman and B.J. Bjorken. Similar discussions were taking place in many other laboratories. We were all looking at the data for the hadronic events in all possible ways, insisting on seeing a hint for charm. Nothing was seen.

As the winter changed into the spring of 1975, there was still no direct evidence for charm, but a new story began to unfold. Martin Perl was one of the leaders of the SLAC-LBL collaboration but he was mostly working on his own, searching for heavy leptons. He was observing a few dozen events which, he thought, showed the production of a single electron, a single muon, and a missing mass. This was the classical signature of a new heavy lepton. At the beginning, he was not sure that he really had a signal. But by April he became bolder and he was spending all his time analyzing and reanalyzing his events, trying to convince his colleagues in the SLAC-LBL collaboration and anyone else who was willing to listen, that he really had something. There were two

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   THRESHOLD: $e^+e^- \to D\bar{D}$ $(W = 4 \text{ BeV})$
   $\boxed{OK}$

② MOST DECAYS INCLUDE K.

   LARGE K/π RATIO.
   $\boxed{K/\pi \text{ IS TOO SMALL}}$

③ $\langle x \rangle \sim 4$, $\langle n \rangle_{ch} \sim 2.7$
   $\boxed{\langle n \rangle_{ch} \text{ IS TOO SMALL}}$

④ $\dfrac{E_{ch}}{E_{tot}}$ NORMAL, BUT "$\dfrac{E_{ch}}{E_{tot}}$" SMALLER.
   $\boxed{OK}$

⑤ INCLUSIVE $e^+e^- \to D\bar{D}$ $\rightarrow x < .5$
   $\quad \hookrightarrow$ HAD.
   $\quad \hookrightarrow$ HAD. $\boxed{OK}$

⑥ $K^-\pi^+$, $K^-\pi^+\pi^+$, etc DECAYS.
   $\boxed{\text{NOT SEEN. UPPER LIMITS ARE TOO SMALL}}$

⑦ SMALL $e\nu$, $\mu\nu$ DECAYS.
   $\boxed{\text{SEEN. RATE TOO LARGE}}$

⑧ $R = 3\frac{1}{3}$ $(+10-20\%)$

$\boxed{\begin{array}{l} \text{EXPERIMENT: } R \sim 5 \\ \qquad\qquad \text{TOO LARGE} \\ \text{THEORY} - \text{ELEGANT.} \\ \text{EXPERIMENTAL DIFFICULTIES} \end{array}}$

Figure 2: The same list of expected properties for charmed meson pairs (see Figure 1) with an overlay describing the actual experimental situation which contradicted the expected properties on points 2, 3, 6, 7, and 8. The text of the overlay, originally in a different color, is emphasized by solid "boxes." A transparency from LP75 [1].
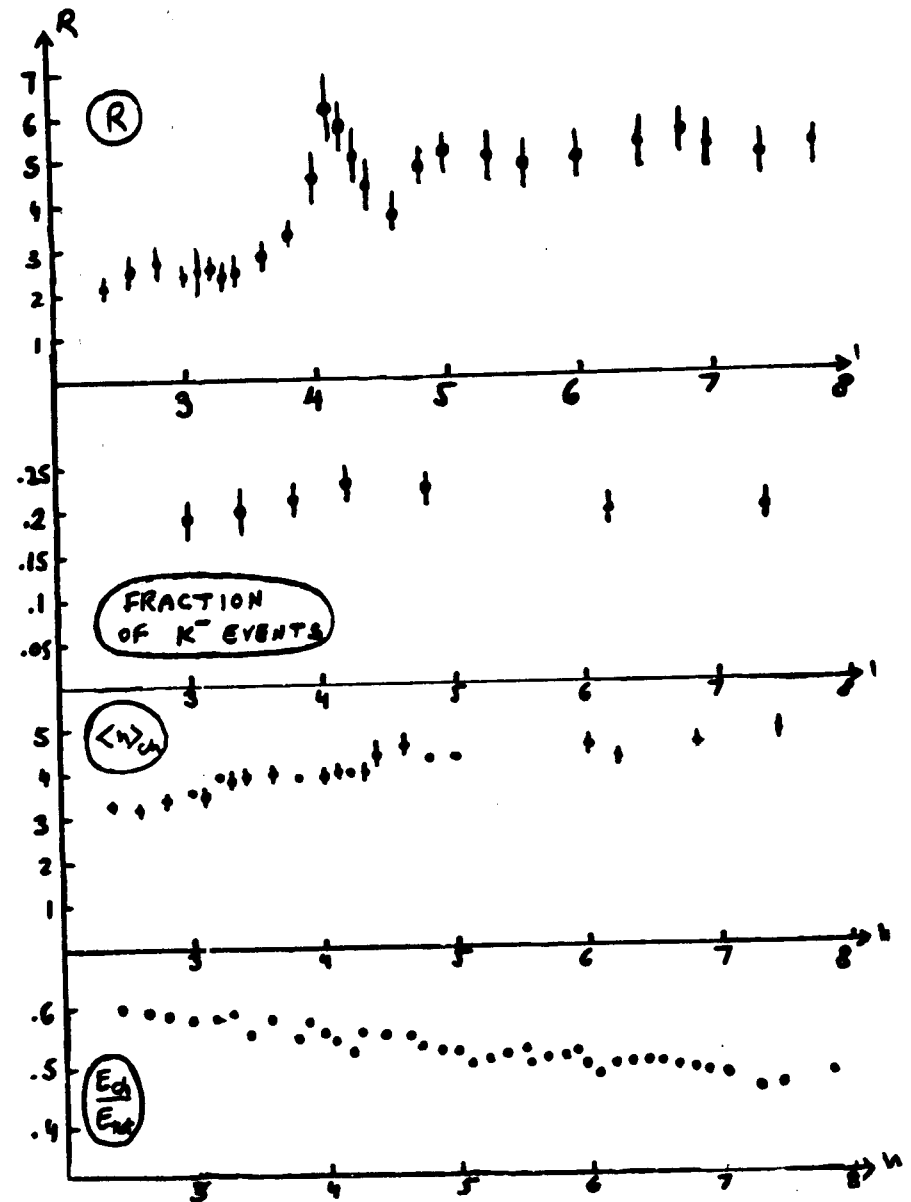
Figure 3: Data available in August 1975 for R, fraction of K events among hadronic events, average charged multiplicity, and fraction of energy carried by charged particles, all plotted against the center of mass energy. A transparency from LP75. The step in R is clearly seen but the new R-value above 4 GeV is around 5. No step is observed in the K-fraction and the multiplicity [1].

unrelated issues here. First, was the experimental identification correct? The alleged muons could have been pions; the electrons could also have been misidentified; the missing mass could have been due to charged particles escaping the detector. A lot of work and a lot of convincing needed to be done before anyone would believe that these were indeed events with exactly one electron, exactly one muon and a missing mass representing only invisible neutral particles (presumably neutrinos). The second issue was: assuming that these were $e\mu$ events, what were they due to?

Most members of the SLAC-LBL collaboration were non-believers. They had several good reasons to doubt Marty's claim. First of all, the particle identification in the detector was quite poor. Second, the solid angle coverage was far from complete, allowing plenty of room for escaping particles. Third, Marty Perl has been trying for years to discover a new lepton. Any claim presented by him sounded suspicious. Everybody knew that, given enough experimental ambiguities, if you searched hard enough for something you would find some evidence for it. No one was going to buy a new lepton from Martin Perl. Finally, the same group with the same experiment and the same data made half a dozen earth-shaking discoveries within half a year. It would have been too much to expect that, on top of everything else, nature would have been so kind as to provide the same people, the same detector and at the same time, with yet another scientific bombshell.

So some of the group members did not listen at all, some listened and argued with Marty, others tried to help him, but no one felt that he had a solid piece of new physics in his hands. Even those who believed that the signal was real, felt that it might simply be due to the decay of the much wanted charmed mesons rather than some new, unrelated esoteric particle.

But Marty continued with the analysis and slowly convinced his colleagues that he could rule out escaping particles, that the probability of particle misidentification was small and calculable and that the events were, indeed, $e\mu$ events. By the end of July 1975 a paper was finally written by Marty and approved by the collaboration [8], claiming the discovery of a new "unknown" particle denoted by U (for Unknown) and decaying into $e\nu$ and $\mu\nu$. Marty wanted to believe that he had a new sequential lepton. Few others, among the group members, believed it at that time.

By August, when the Lepton-Photon Conference was approaching, the search for the charmed meson, or at least for the smoking gun which would be clear circumstantial evidence for it, was intensifying. Nothing was found and, in spite of improved statistics, all the negative features remained: no increase in strange particles or in multiplicity, no $K\pi$ or $K\pi\pi$ peaks, too many $e\nu$ and $\mu\nu$ events and too much hadronic cross section. The

Perl events were an unnecessary added confusion in a puzzle that was bad enough without them.

But then, suddenly, everything fell into place. There was no evidence for charmed mesons and feeble evidence for a heavy lepton. But, if the Perl events indeed represented a new lepton, how would that change the theoretical expectations (Figure 4)?

(1)   A heavy lepton would also contribute a step in the total cross section into hadrons (since most of its decays are hadronic decays). If the mass of the new lepton would also be around 2 GeV, the observed step would then be due to both charmed meson production and lepton pair production and the "new physics" above 4 GeV would include two unrelated components: pairs of charmed mesons and pairs of heavy leptons.

(2)   A heavy lepton would decay into strange particles only 5% of the time (K/π ratio determined by $\sin^2\theta_c$), well below the standard K/π ratio of non-charmed hadronic events. Therefore, the "new physics" component above 4 GeV would have one part (charmed mesons) which was dominated by strange particles and another part (heavy leptons) which had very few strange particles, leading to an average strange particle yield which was comparable to that of the "old" hadronic component below 4 GeV.

(3)   The average charged multiplicity in the decay of a heavy lepton would be about 1.5, well below the normal charged multiplicity of a hadronic event. So, again, the newly discovered physics would include a piece (charmed mesons) with very high multiplicities and a piece (heavy leptons) with very low multiplicities, averaging out to the normal hadronic multiplicity and showing no clear change as one goes through the 4 GeV threshold.

(4)   All heavy lepton decays involved a neutrino. Therefore no peaks in invariant mass plots were expected for the heavy lepton. The charmed meson peak would then become less prominent because half of the events are not charmed events and because the charmed meson decay multiplicity could now be quite large, diminishing the probability of exclusive two-particle and three-particle decays. So the absence of peaks was not disturbing any more.

(5)   The observed $e\nu$ and $\mu\nu$ events were indeed numerous because they all came from heavy lepton decays and not from charmed meson decays.

$$e^+ + e^- \rightarrow U^+ + U^-$$

with decays:
$$\hookrightarrow e^+ \quad \hookrightarrow \mu^-$$
$$\hookrightarrow \mu^+ \quad \hookrightarrow e^-$$
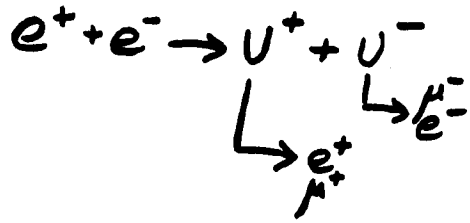
$U^\pm$: HEAVY LEPTON?

1. MASS ~ 2 BeV
   THRESHOLD: $e^+e^- \rightarrow U^+U^-$ (W$\sim$4BeV)

2. $\frac{K}{\pi}$ RATIO VERY SMALL ($\lesssim 5\%$)

3. $\langle n \rangle_{ch} \sim 1.5$

4. $\frac{E_{ch}}{E_{tot}}$ SMALL (<0.5)

5. $15-20\%$ $\begin{cases} e^- \bar{\nu}_e \nu_U \\ \mu^- \bar{\nu}_\mu \nu_U \end{cases}$

6. $\Delta R = 1$

$$e^- \nu \bar{\nu}$$
$$\mu^- \nu \nu$$
$$\pi^- \nu$$
$$\pi^- \pi^0 \nu$$
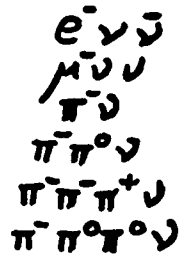$$\pi^- \pi^- \pi^+ \nu$$
$$\pi^- \pi^0 \pi^0 \nu$$

Figure 4: Expected properties of events due to the production of pairs of heavy leptons. It is clear that many of the properties are opposite to those described in Figure 1 for charmed mesons. A transparency from LP75 [1].

(6)   The expected value of R would now be a little over 4 with the same ambiguity of 10%–20%, just consistent with the observed experimental R-values which were around R = 5.

So, by making one crazy assumption about the simultaneous existence of a heavy lepton and a charmed meson threshold in the same energy range, we could suddenly understand [1] all the puzzles related to the absence of charmed mesons (Figure 5).

This was a remarkable situation. Suddenly the absence of a smoking gun was a proof that we had two murderers. One committed the crime and left a smoking gun. The other came to the same place, at the same time, committed a second crime, picked up the gun and disappeared. Think about a story in which the famous detective finds no gun and immediately concludes that this clearly proves that there were two different unrelated criminals. Would you believe such a story? "Nonsense," you would have said. We had no direct evidence either for heavy leptons or for charmed mesons, but we could interpret it as circumstantial evidence for the existence of both. The step in the value of R was clear evidence that something new was happening. The absence of striking changes in other quantities indicated that the new "something" was really due to two unrelated different objects, cancelling each other's effects.

But now we had a new problem. Remember the reasons for predicting the fourth charmed quark. They were directly related to the leptonic pattern of two generations of SU(2) doublets. If the charmed quark indeed existed in the SLAC-LBL data, it was a wonderful triumph for the theory, based on the existence of four leptons. But if, at the same time, a fifth lepton was discovered, everything was lost. . . unless additional quarks existed. So the solution of the puzzle led to a further prediction: the fifth lepton should be accompanied not only by its own neutrino (like the electron and the muon), but also by an additional pair of quarks, needed for the elimination of anomalies in the electroweak gauge theory. The full theory would then require six leptons (of which we then had definite four and an alleged fifth) and six quarks (of which we had definite three and an alleged fourth). The two additional quarks were named top and bottom in a paper [9] which preceded the correct solution of the puzzle and which was written in the height of the confusion caused by the absence of charmed mesons.

In August 1975 most people did not really believe that this was the correct solution of the puzzle. But now we know that the scenario presented then [1] was precisely the correct one (Figure 6). Less than a year later, the charmed meson peaks were discovered [10]; by 1977 the τ properties were confirmed and the two component explanation of the new physics above 4 GeV, was accepted by all; the fifth quark came soon after [11].

D-SPECTROSCOPY

① MASS ~ 2 BeV ✓
   THRESHOLD : $e^+e^- \to D\bar{D}$ (W = 4 BeV) [OK]

② MOST DECAYS INCLUDE K.
   LARGE K/π RATIO.
   [K/π IS (NOT) TOO SMALL]

③ $\langle n \rangle \sim 4$, $\langle n \rangle_{ch} \sim 2.7$
   [$\langle n \rangle_{ch}$ IS (NOT) TOO SMALL]

④ $\frac{E_{ch}}{E_{tot}}$ NORMAL, BUT " $\frac{E_{ch}}{E_{tot}}$ " SMALLER. [OK]

⑤ INCLUSIVE $e^+e^- \to D\bar{D}$
   $\hookrightarrow$ HAD. $\to x < .5$
   $\hookrightarrow$ HAD. [OK]

⑥ $K^-\pi^+$ $K^-\pi^+\pi^+$, etc DECAYS.
   [NOT SEEN. UPPER LIMITS ARE (NOT) TOO SMALL]

⑦ SMALL $e\nu, \mu\nu$ DECAYS.
   [SEEN. RATE (NOT) TOO LARGE]

⑧ $R = 3\frac{1}{3} (+10-20\%) + 1 = 4\frac{1}{3} (+10-20\%)$
   [EXPERIMENT : $R \sim 5$
     (NOT) TOO LARGE
     THEORY - (IN)ELEGANT.
     (NO) EXPERIMENTAL DIFFICULTIES]

Figure 5: The original list of predictions for charmed meson pairs (Figure 1) with the overlay describing the disastrous results of the data (see Figure 2) and yet another overlay describing how the situation changes as a result of the additional existence of a new heavy lepton. Most predictions are simply reversed and the new situation is in total agreement. The first overlay is shown in rectangular solid "boxes" and the second overlay in solid circles. A transparency from LP75 [1].

SUMMARY

BEST BET :
   EXPERIMENT $\to u, d, s, c$
   $\binom{e}{\nu_e} \binom{\mu}{\nu_\mu} \binom{\nu}{\nu_\nu}$

   THEORY $\to t, b$

① VERIFY THAT U IS A LEPTON.

② FIND D-MESONS

③ Υ SPECTRUM

① V+A ?

② HOW MANY QUARKS AND LEPTONS?

③ QUARK-LEPTON RELATION.

Figure 6: The summary transparency from LP75. The claim is made that the data contains four quarks (including charm) and six leptons (including τ and ν_τ), and that the theory now requires two more quarks, b and t. "Things to do" are listed at the bottom left and open questions on the bottom right [1].

Now, a few million τ leptons later, we have come a long way since the handful of events of Marty Perl in 1975. Experiments are now observing huge numbers of rare τ decays which no one would have dared to dream about in 1975. For instance, the CLEO collaboration now has 400 observed events [12] of $\tau^{\pm} \to \pi^{\pm}\pi^0\pi^0\pi^0\nu_\tau$! To the SLAC-LBL old-timers this appears unbelievable. Every once in a while we have a τ branching ratio which appears to be two standard deviations away from the theoretical prediction and we hope that finally something will go wrong with the standard model. But that has not happened yet.

We are looking forward to the possibility of constructing a τ factory which, strangely enough, will not only teach us about the τ lepton but will also help solve problems related to hadron physics, weak interactions, etc. In fact, a τ factory may be viewed as a lepton-neutrino collider since the reaction $\tau \to \nu_\tau$ + anything is conceptually equivalent to the reaction $\tau + \nu_\tau \to$ anything, producing charged final states analogous to the neutral ones which are produced in e^+e^- collisions.

The τ particle was the first particle of the third generation of quarks and leptons. The b-quark followed in 1978. The two other fermions of the same generation are still missing; no one has seen a ν_τ or a t-quark, but few people doubt their existence. We all believe that it is just a matter of time until they are discovered.

We already know that the third generation is the last one with a light neutrino and it is probably the last one with any kind of neutrino. One of its particles, ν_τ, may actually be the cosmological dark matter of the universe, in which case most matter in the universe is third generation fermions. The t-quark, being the heaviest fundamental fermion, may be the "driver" of the mechanism responsible for fermion masses. It is possible that the third generation is not just a footnote to the story of the structure of matter. It may play a very crucial role in understanding the universe.

We are still very far from understanding the generation puzzle, the difference among the generations, and the reasons for their existence and for their number. One day we might discover some deviation from universality, perhaps some kind of a horizontal symmetry or some other fascinating experimental clue which will shed some light on this question. Perhaps there is some substructure which determines the difference between the generations; perhaps some other mechanism. But it all started with a few events, an excellent stubborn experimentalist, a good experiment, and a third rate detective plot which no one would have believed, if it did not happen in real life.

I thank Martin Perl for sharing with me his thoughts, his doubts, and his events in 1975, and for teaching all of us a lesson in the art of doing physics.

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