Charm Quark
Bottom Quark
Top Quark
Are there more lepton-quark generations?
**Charm Quark: discoverers**

**Early 1970s**

Leon Lederman with collaborators studied $p^+N \rightarrow \mu^+\mu^-X$ and found what appeared to be a small shoulder in $dN/dM_{\mu\mu}$ spectrum (a sharply falling distribution), but it was on a borderline of being significant and was discarded...

**August 1974**

Samuel Ting with collaborators studies $p^+Be \rightarrow e^+e^-X$ at 33 GeV AGS machine at Brookhaven and found a pronounced narrow resonance with $M_{ee} \sim 3$ GeV, but keep it secret and carry out lots of cross-checks. They called it $J$. The width was apparently much smaller than their detector's resolution...

**Meanwhile**

Burton Richter with collaborators continue their studies of $R = \sigma(e^+e^- \rightarrow \text{hadrons}) / \sigma(e^+e^- \rightarrow \mu^+\mu^-)$ at $\sqrt{s}=2.5-7.5$ GeV at just recently commissioned SPEAR $e^+e^-$-collider at Stanford. The goal was to follow up on earlier measurements obtained at Frascati and Cambridge in 1973 showing substantial rise in $R$ to $\sim 6$.

July

At the conference in London, they just reported that indeed $R$ scanned with steps of 150-200 MeV had some jumps at $\sqrt{s} > 3$ GeV.
Fall 1975  **Richter** group proceeded scanning with a 100 times smaller step of 2 MeV and stumbled on an extremely narrow peak at the center of mass energy $\sqrt{s}=3.1$ GeV ($\psi$).

Nov 11 (weekend) 1974  **Ting** arrives to Stanford with intention to go public with the discovery and learns that **Richter**'s group also sees probably the very same resonance.

Swarm of papers theorizing about what the narrow resonance might be—charm-anticharm bound state ($J=1$; $L_{qq}=0$, $S_{qq}=1$) is the winner… The particle is named $J/\psi$. Its width $\Gamma$ is only 0.09 MeV. Such a width implies lifetime of $10^{-20}$ s.

(in two weeks) 1974  **Richter** group finds another narrow resonance at $\sqrt{s}=3.7$ GeV ($\psi'$).

1976  **Ting and Richter** are awarded Nobel Prize "for their pioneering work in the discovery of a heavy elementary particle of a new kind"

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**Curious note:** 1974  Iliopoulos bet a case of wine on his prediction that the charm quark would be discovered within a year! This was at the summer conference of 1974, just a few months of what would have become known as November Revolution...
Charm Quark: hunt for "open charm"

Note: $\phi ( \bar{s}s ) \rightarrow K^+ ( \bar{s}u ) + K^- ( \bar{u}s )$. Why is similar decay into open charm states is not observed for $J/\psi$? Is mass of the two similar open charm particles, $D^- ( \bar{c}d ) + D^+ ( \bar{d}c )$, too large?

1975-76 Open charm rush:
- Looking for candidates in emulsions, bubble chambers, press-conferences, headlines, no strong evidence.
- **Japan**: emulsions exposed in cosmic rays: a few events with particles of very short lifetime ($\Delta \sim 10^{-10\ldots10^{-13}} \mu m$, or $\tau \sim 10^{-12\ldots10^{-13}} s$)
- **BNL**: bubble chamber pictures ($\nu_{\mu} + N \rightarrow ???$)
- **FNAL**: $\nu + N \rightarrow di-leptons + X$

After reconstructing the masses, one of the 3 possible $\Lambda^0 \pi^+ \pi^+ \pi^-$ combinations give Mass($\Sigma_{c}^{++}$) – Mass($\Lambda_{c}^+$) = 166 MeV, consistent with the classical baryon decuplet mass splitting...

1976 **Goldhaber and Pierre** finally found an open charm particle $\bar{u}c$, or $D^0$, as a resonance-like peak in $K^+\pi^-$ distributions at SPEAR at Stanford, its mass being 1.865 GeV. The bump was appearing only after reaching a threshold of producing two $D$-mesons.

1977 Other lowest mass charm mesons are discovered: $\bar{d}c (D^*)$ and $\bar{s}c (D_s)$. Charmed baryons...
Their displayed vertices measured in precision bubble chambers turned out to correspond to lifetimes of the order of a few tenths of ps ($c$-quarks decay via $c \rightarrow d W^+$).

Four-quark multiplets now have to be drawn in three dimensions. We will not bother with this…
Bottom/Beauty Quark

1975  \(\tau\)-lepton is discovered at SPEAR, Stanford
The 3\textsuperscript{rd} generation of quarks is around the corner!

1976  \textbf{Leon Lederman}, basically having missed J/\(\psi\) in his muon spectrometer at Fermilab, is now anxious to scoop out the bottom quark. The rush "discovery", PRL 36 (1976) 1236 has become known as the "Oops-Leon" particle.

1977  \textbf{Leon Lederman}, finally pins it down unambiguously (PRL 252 (1977) 39): \(b\bar{b}\)-bound state as \(\mu\bar{\mu}\)-resonance in \(p+N\rightarrow \mu\bar{\mu}\ X\). The particle is named \(\Upsilon\) (Upsilon\textsuperscript{1}). It is in one-to-one correspondence to J/\(\psi\). Its mass is about 9.5 GeV (and, therefore, \(m_b\approx 4.5\) GeV\textsuperscript{2}).

1978  DORIS at DESY is upgraded to reach the energy needed to create \(\Upsilon\) in \(e^+e^-\) collisions. The resonance is confirmed to be very narrow and has mass 9.46\(\pm 0.01\) MeV. Further upgrades pushed \(\sqrt{s}\) energy even higher and one more \(\Upsilon'\) resonance showed up at \(\sqrt{s}=10.00\) GeV. Mass split between \(\Upsilon'\) and \(\Upsilon\) is exactly the same as between \(\psi'\) and J/\(\psi\).

1980  CESR at Cornell discovers another narrow \(\Upsilon''\) (10.32 GeV) and yet one more but now broad \(\Upsilon'''\) (10.58 GeV) resonances. The broad one decays into open beauty \textbf{B-mesons} ("naked beauty" or "bare bottom"?). Open beauty mesons live \(\approx 1\) ps. Their decay modes are \(b\rightarrow c\ W^-\) (dominant) and \(b\rightarrow u\ W^-\).

Charm and Beauty spectroscopy flourished:
s-states: \(\Upsilon\) (1s), \(\Upsilon'\) (2s), \(\Upsilon''\) (3s), \(\Upsilon'''\) (4s),
p-states confirmed in radiative decays such as \(\Upsilon'\rightarrow \chi_b\ \gamma\)
Heavy Quark Effective Field Theory, HQEFT, born.

1  And thus his 1976 "discovery" has become known as "Oops-Leon" particle...
2  Lederman does not get Nobel Prize for this—he already has one for the muon neutrino discovery!
Top Quark

B-mesons live ~1.3 ps, which is actually longer than D-mesons (and this is despite the much larger phase space available in their decay channels). This lucky feature will be explained when we discuss the nature of phenomenon of quark mixing, GIM mechanism, and related physics. This is not the case for the top-quark. In combination with its much larger mass, it decays so fast that it never gets a chance to become a real hadron! The weak interaction decay actually has

The fact that top-quark turned out to be somewhat higher (in log scale—see the pattern of the SM fermion masses) resulted in many unsuccessful searches and a lot of despair: faulty discovery at CERN by UA1, construction of TRISTAN collider in Japan, lengthy search at Tevatron…

1994 Finally (in long 17 years after b-quark discovery!), the evidence for the top-quark existence of emerged at Tevatron, Fermilab. CDF and D0 Collaborations reported signs of the top-quark with the mass of 175±5 GeV—the heaviest elementary particle ever known (so far). After 9 months of secrecy, cross-checks, 8 drafts of 195-page paper with 65 graphs, CDF releases the news in April of 1994³. The key words for the paper title considered by the collaboration were "study", "evidence", "discovery", "observation", … The choice goes for "evidence". The significance was below 3σ…

1995 Both CDF and D0 follow up with two papers now calling for "discovery of top-quark".

- Top quarks are born in pairs: \( \bar{t}t \) and \( t \bar{t} \).
- Top quark's dominating mode of decay is \( t \rightarrow Wb \):
  - b-quarks give b-tagged jets (jets with a secondary vertex displaced by ~100 \( \mu \)m or so and corresponding to a B-meson decay)
  - W can decay into either quark-antiquark or lepton-neutrino pair

Therefore, \( \bar{t}t \) pair production can look like one of the following:

- 3+3 jets, with two jets tagged as b-jets: most probable, but very large QCD background!
- 2 leptons of different signs (and possibly flavors!), 2 b-jets, and missing energy: golden but rare event!
- 1 lepton, 4 jets (two of which are b-tagged), and missing energy: more frequent with fair background

Actually all these channels had to be used with proper weights to see "the evidence" and make "the discovery".

³ D0 publishes their results at the same time (not by accident, of course).
Are there more generations beyond the three that we know of?

mid-1980 New race between US and Europe for $e^+e^-$ collider with $\sqrt{s}=91.2$ GeV to study $Z$ particle:
- precision tests of the EW Theory, in general,
- and, in particular, counting the number of quark-lepton generations via measuring $Z$-boson production cross section and its width: $\Gamma = \Gamma(Z\rightarrow q\bar{q} \nu\bar{\nu}) + \Gamma(Z\rightarrow l^+l^-) + \Gamma(Z\rightarrow \nu\bar{\nu})$

CERN picks a conventional technology of building large storage rings, LEP (27 km in circumference)...

SLAC bets on an innovative idea of converting their linear accelerator into a collider by adding two arches. The luminosity will be much lower than at LEP, so to be the first is the key...

1987 SLAC turns on, but initially has serious troubles in focusing (a few $\mu$m size needed!) and guiding the beams... Nevertheless, slowly but steadily the luminosity improves. By summer 1989, SLAC produces a few hundred $Z$-bosons... Just enough to measure the $Z$-line width and determine the number of light neutrinos...

1989 LEP turns on as a clock in August...

Sep 1989: SLAC holds a press-conference announcing the number of neutrino species being 3...
This is done one day before LEP announces the same result with much better statistics...

Plot below is based on full LEP statistics: curves from top to bottom correspond to $N_\nu=2, 3, 4$.
Fit gives $N_\nu=2.994\pm0.012$.

Note that the $Z$-line width can be used to count only neutrinos with masses less than ~45 GeV. However, combined with the cosmological constraints on the sum of masses for all types of neutrinos $\Sigma m_i < 2$ eV, this measurement does constraint the number of generation to be 3, independently on charged lepton and quark masses in would-be extra generations.