The discovery of the top Quark: Lina Galtieri, Feb 5-2020

THE DISCOVERY OF THE TOP QUARK

Lina Galtieri (LBNL)

- Historical review of particle discoveries.
- Cosmic Rays gave the first information about particles beyond the electron and the proton.
- 1955: the first accelerators were developed by Lawrence, here at Berkeley (pbar discovered)
- 1960: the Hydrogen Bubble Chamber developed by L. Alvarez at LBL, allowed finding many particles.
- 1964: Gell-Mann and Zweig developed the quark model SU(3) Symmetry) to explain the existence of these particles.
- 1967-70 Glashow, Weinberg and Salam proposed the Standard Model
- 1973 Neutral Currents were found.
- 1974: The J/psi, bound state of c-c quarks is found
- 1975: the tau lepton was observed, confirmed in 1977
- 1977: the bottom quark is found
- 1995: the top quark is found

The building blocks of matter today.
u, d, s and t are the ones LBL contributed the most.
Before 1960 most particles were discovered with cloud chambers or nuclear emulsions. By 1959 a new detector (Alvarez’ hydrogen bubble chamber) was built at LBL. The first particle discovered was the $\Xi^0$

After the $\Xi^0$ 18 more particles were discovered or co-discovered in the Alvarez’ hydrogen bubble chambers

The $\Xi^0$ is a “stable” (lifetime $\sim 10^{-10}$sec) particle, while the other 18 are resonances i.e. they decay in a very short time.
The neutron decay into a proton was the beginning of particle physics. It is called a fermion because Enrico Fermi was the first to observe this decay.
Lawrence invented the accelerators. The Bevatron accelerated protons up to 6.2 GeV into a copper target. One of the experiments proposed there, was a p-p collision study by the Segré group. They found the antiproton in 1955, for which they were awarded the 1959 Nobel Prize in physics (E. Segré, O. Chamberlain and T. Ypsilantis).

A stack of nuclear emulsions was also exposed to the negative particle beam generated by the collision of the proton beam into a target. The antiprotons were distinguished from the produced pions using the time of flight (40 ns) for pions, vs 51 ns for pbar.
I came to LBL from the University of Rome in 1961, first working in a group that used nuclear emulsions as detector, but in 1962 I moved in the Alvarez group. The bubble chamber was the new detector installed in the newest accelerator: the Bevatron (6.2 GeV).

Both the $\Lambda$ and $\bar{\Lambda}$ were already known. Here we see a picture of one event in the HBC: an antiproton colliding with a proton and producing a $\Lambda$ and an $\bar{\Lambda}$

$$\bar{p} p \rightarrow \Lambda \bar{\Lambda}$$

19 new particles were discovered in the bubble chamber. Both protons and antiprotons beams were used. Also beams of K mesons were used for searches of new particles containing a strange quark (like the K meson).

These particles were called strange because they decay in a very short time.
Resonances: 8 by the LRL (now LBL) group, 10 co-discovered by LBL or by groups who used the LBL film

\[ \Sigma(1385) \] and \( Y^*(1405) \)

- \( Y^*(1385) \) baryon LRL 1960
- \( K^*(890) \) meson LRL 1960
- \( Y^*(1405) \) baryon LRL 1960
- \( \rho \) meson BNL+ LRL 1961
- \( \omega \) meson LRL 1961
- \( \eta \) meson JH/NW +LRL 1961
- \( Y^*(1520) \) baryon LRL 1962
- \( \phi(1019) \) meson BNL/SY/UCLA 1962
- \( Y^*(1660) \) baryon LRL 1962
- \( X^*(1530) \) baryon UCLA/BNL/SY 1963
- \( Y^*(1765) \) baryon LRL 1963
- \( A1 \) meson GT +LRL 1964
- \( A2 \) meson GT +LRL 1964
- \( \eta' \) meson BNL/SY+LRL 1964
- \( D(1285) \) meson LRL 1965
- \( X^*(1815) \) baryon EUC+LRL '65
- \( Y^*(2100) \) baryon BNL+LRL '66
- \( Y^*(2030) \) baryon BNL+LRL '66

Alston et al.
Nishijima and Gell Mann had predicted the $\Xi^0$ existence

$K^- p \rightarrow K^0 \quad \Xi^0$
The $\Lambda$ and the $\Xi^0$ seen earlier have a lifetime of $\approx 10^{-10}$ sec. They decay into other particles, and we can see a gap in the film.

A new class of particles, the resonances, decay in a very short time ($10^{-23}$ seconds), no gap is seen. The resonances are found by a peak in the T of a particle in the event.

Here is the first resonance seen in HBC by “Bump Hunting”.
Discovery by: Alston, Alvarez, Eberhard, Good, Graziano, Ticho, Wojcicki

Only one resonance $\Delta^{++}(1232) \rightarrow$ proton+pi+ was known before the HBC were constructed. This was discovered by the Fermi group at Chicago (1952).
Luis Alvarez won the Nobel Prize in Physics in 1968 for his contribution to particle physics and with the development of the hydrogen bubble chamber and data analysis.

The small bubble chambers used for the discoveries. The 72” is partially shown here.

Luis invited his closest collaborators to go to Stockholm with him to participate to all activities associated with the Nobel Prize. We were among the eight couples that went with him and his family.

Lina Galtieri and Luis Alvarez in 1977
The Birth of the Quark Model

Which particles were known in 1950?
Proton, neutrons, electrons, that comprised the atom
Leptons(light particles): electrons, muons, neutrinos
Hadrons(heavy particles): proton, neutrons

What about all these new particles? Can we find a way to classify them with a few building blocks?
Gell-Mann chose the whimsical name of “quarks” for these constituents. This word appears in the phrase “three quarks for Muster Mark” in James Joyce’s novel Finnegans Wake. It was also called ‘The eightfold way’, a saying of the Buddha about the eight ways to reach Nirvana.’
The same scheme was suggested by Yuval Ne’eman.

The quarks required a charge +2/3 and -1/3 of the charge of the proton. No fractionally charged objects had been observed, so this was a revolutionary suggestion. At first the quarks were regarded as a mathematical fiction, but experiment have convinced physicists that quarks do exist. Zweig came up with the same model. The 1969 Nobel Prize was awarded to Gell-Mann and Zweig.

Murray Gell-Mann
Mesons are made with two quarks.

This entire nonet was discovered \((K^*, \omega)\) or co-discovered \((\rho, \phi)\) in Luie's bubble chambers.
BARYON MULTIPLETS

Baryons are made of three quarks.

SU(3) algebra expects:

\[ 3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1 \]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Quark content</th>
<th>Electric charge</th>
<th>Mass GeV/c²</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>proton</td>
<td>uud</td>
<td>1</td>
<td>0.938</td>
<td>1/2</td>
</tr>
<tr>
<td>( \bar{p} )</td>
<td>antiproton</td>
<td>( \bar{u}\bar{u}\bar{d} )</td>
<td>-1</td>
<td>0.938</td>
<td>1/2</td>
</tr>
<tr>
<td>n</td>
<td>neutron</td>
<td>udd</td>
<td>0</td>
<td>0.940</td>
<td>1/2</td>
</tr>
<tr>
<td>( \Lambda )</td>
<td>lambda</td>
<td>uds</td>
<td>0</td>
<td>1.116</td>
<td>1/2</td>
</tr>
<tr>
<td>( \Omega^- )</td>
<td>omega</td>
<td>sss</td>
<td>-1</td>
<td>1.672</td>
<td>3/2</td>
</tr>
</tbody>
</table>

JP=1/2\(^{+}\) Baryon nonet

The discovery of the top Quark: Lina Galtieri, Feb 5-2020
Baryons and Mesons

The omega was discovered in 1964. Its mass is $M = 1672$ MeV.

Too heavy to be seen at LBL.

SU(3) complete!

u d s
1967-1970: Glashow, Weinberg and Salam hypothesized the Standard Model, unifying all that we knew at the time: QED (e.m.), Weak interactions (W,Z) Strong interactions (Gluon)

They received the 1979 Nobel Prize

Glashow, xxxx, Rosenfeld
At CERN Rubbia found the W and Z in 1973. Carlo Rubbia was working at FNAL on the p-pbar collider, but the energy was not sufficient to discover the W and the Z. He went to CERN and got the funds for a collider there, thus found both the W and Z! Rubbia received the Nobel Prize in 1984.
Discovery of the charm quark

So far we have dealt with 3 quarks, (SU(3)), but eventually the number of quarks will go up to 6, including the top quark.

Charm discovered at SLAC on November 11-1974 and at BNL by Sam Ting. The 3 peaks are due to a c-cbar bound states.

Bert Richter and Sam Ting were awarded the Nobel Prize for the charm quark discovery in 1976.
More charm

The SLAC e+ e- machine collided the beams at higher energy and new peaks showed up: the first sharp one, is due to open charm, i.e, the production of a pair of charmed mesons: D0 and D0bar.
Meson and Baryons from udsc quarks

Mesons with d u s c quarks

Baryons with d u s c quarks

More multiplets containing the b quark have been discovered
The tau lepton was observed at SLAC in 1975, in the Mark I detector the same detector where the charm quark was discovered.

For the tau lepton was necessary to identify events with e or mu. Better electron identification was needed. A lead glass detector served the purpose. The tau lepton was confirmed in 1977

Martin Perl got the 1995 Nobel Prize for the discovery of the tau lepton.
The bottom quark was found at Fermilab.

Lederman’s group found many bound states of $b$ and $b$-bar like the charmonium states.

The 1988 Nobel Prize was awarded to Lederman.
At this point most of the standard model elements had been seen. The gluon and the top are missing.

The gluon was discovered in 1979 at DESY by the TASSO Collaboration. They used the PETRA collider operating at 27.4 GeV.
Missing quark (the top)

The Standard Model

- Leptons
  \[
  \begin{pmatrix}
  \nu_e \\ e \\
  \nu_\mu \\ \mu \\
  \nu_\tau \\ \tau
  \end{pmatrix}
  \begin{pmatrix}
  0 \\
  -1 \\
  ? \\
  +2/3 \\
  -1/3 \\
  \end{pmatrix}
  \]

- Quarks
  \[
  \begin{pmatrix}
  u \\ d \\
  c \\ s \\
  t \\ b
  \end{pmatrix}
  \begin{pmatrix}
  +2/3 \\
  -1/3 \\
  \end{pmatrix}
  \]

- Gauge Bosons
  Mediators of the fundamental forces

<table>
<thead>
<tr>
<th>e.m.</th>
<th>Q</th>
<th>M</th>
<th>Spin</th>
<th>Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>QED</td>
</tr>
<tr>
<td>weak</td>
<td>0</td>
<td>90 GeV</td>
<td>1</td>
<td>Weak</td>
</tr>
<tr>
<td>Z⁰</td>
<td>0</td>
<td>90 GeV</td>
<td>1</td>
<td>QCD</td>
</tr>
<tr>
<td>strong</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>QCD</td>
</tr>
</tbody>
</table>

Masses very different → broken symmetry → Higgs Mechanism

TOP SEARCHES

1. e⁺e⁻ colliders
   - Tristan (1988) \( M_{top} > 28 \) GeV
   - SLAC, LEP (1990) \( M_{top} > 44.8 \) GeV

2. Hadron Colliders (this talk)

1983-1985
   - CERN \( p\bar{p} \) collider (\( \sqrt{s} = 546, 630 \) GeV)
     - 0.7 pb⁻¹ - collected by UA1 \( \rightarrow M_{top} > 41 \) GeV

1988-1989
   - CERN \( p\bar{p} \) collider (\( \sqrt{s} = 630 \) GeV)
     - 4.7 pb⁻¹ - collected by UA1 \( \rightarrow M_{top} > 61 \) GeV
     - 6.4 pb⁻¹ - collected by UA2 \( \rightarrow M_{top} > 69 \) GeV
   - FNAL \( p\bar{p} \) collider (\( \sqrt{s} = 1800 \) GeV)
     - 4.4 pb⁻¹ - collected by CDF \( \rightarrow M_{top} > 89 \) GeV

@ 95% CL
Where is the top?

LG talk at DESY (October 1-1990)

I. INTRODUCTION

- Top Production (in lowest order)

$$\begin{align*}
\bar{b} &\rightarrow t \, W
\end{align*}$$

electroweak

$$m_t < m_W + m_b$$

dominant at Tevatron

even for $$M_t \sim 60 \text{ GeV}$$

- Will discuss
  a. Rates
  b. Topology
  c. Physics Background

A. Rates

- W cross section relevant for $$M_t \approx 70 \text{ GeV}$$
  - Calculated by Altarelli et al. in higher order QCD
  - Measured at both CERN and FNAL
- Hard scattering

$$\begin{align*}
\text{Higher order calculations done by Nason, Dawson and K. Ellis [NP. B303, 607 (88)] - K factor for top } &\approx 1.5.
\end{align*}$$

- Note that this uses only 1 set of structure functions. Uncertainty can be larger
- Note that at 1.8 TeV hard process dominates over the electroweak
Apologies to my D0 colleagues. At LBL there were two different groups working at FNAL in the top search.

I can only talk about the search in the CDF collaboration. The results from the D0 collaboration will be shown at the end.
A lot of efforts went into improving the detectors and the trigger system at CDF and D0 (LBL was participating in both experiments).

A silicon vertex detector (SVX) was designed and built (Pisa and LBL) and installed in the CDF detector. This improved track reconstruction and allowed to reconstruct the top decay position.
This event was found in the CDF detector on September 1992.

The reconstructions of the tracks shows the two bottom jets at a distance from the collision point.

It took about 3 years before the announcement of the discovery was made. One event was not enough for the world to accept the discovery.
The CDF discovery results

Top mass distribution with 7 tagged events in run1.

\[ M(\text{top}) = 174 \pm 10 \pm 12 \text{ GeV} \]

SUMMARY and CONCLUSIONS

- We observe:
  - DIL: 6 events backg. = 1.3\pm0.3 \quad P=3\times10^{-3}
  - SLT: 23 tags backg. = 15.4\pm2.0 \quad P=6\times10^{-2}
  - SVX: 27 tags backg. = 6.7\pm2.1 \quad P=2\times10^{-5}

  total of 43 top events candidates

- Combined significance: \( 1 \times 10^{-6}(4.8 \sigma) \)
- We observe a sharp peak and measure:

\[ M_{\text{top}} = 176 \pm 8 \pm 10 \text{ GeV/c}^2 \]

- A simple KS test gives a probability of 2\% that the mass distribution agrees with a background hypothesis
- Combined significance:

\[ P=4 \times 10^{-7}(5.0 \sigma) \]

TOP IS DISCOVERED
The top mass

The top mass results from 1970:

- $M_{top} = 176 \pm 13 \text{ GeV/c}^2 \quad \text{CDF 1995}$
- $M_{top} = 199 \pm 30 \text{ GeV/c}^2 \quad \text{D0 1995}$

The error on the expected Higgs mass is very large!
The b quark was discovered in 1977. It took 18 years to find the top quark. The search was pursued all around the world, from Tristan to SLAC to CERN to Fermilab! Finally the top quark was found in 1995!

24 years later (on July 2019) the European Physical Society awarded to the CDF and D0 collaborations a prize for the discovery.