Discovery of c, b and t quarks and quarkonia

Marco Schramm

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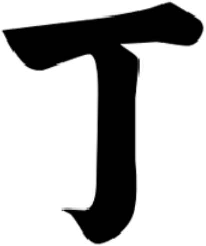

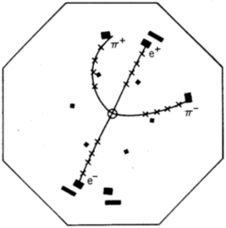

Outline

- Introduction
- November Revolution / Discovery of the Charm Quark
- Quarkonium
- Discovery of the Bottom Quark
- Discovery of the Top Quark

Quarks

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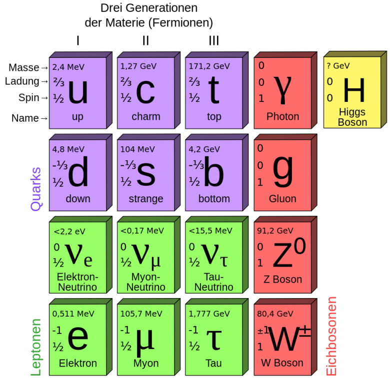
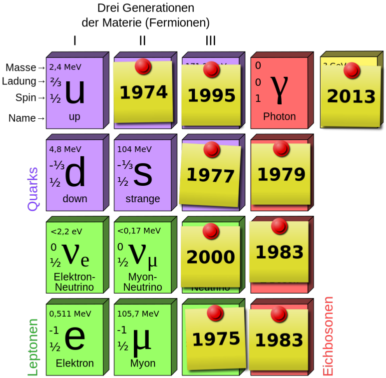


http://de.wikipedia.org/wiki/Standard-Modell

- 6 different quarks

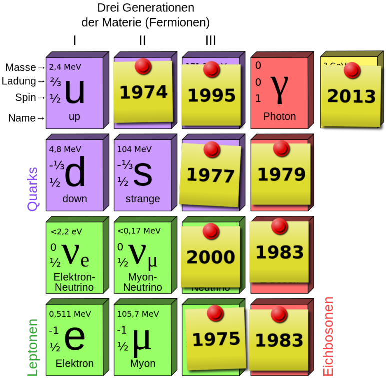
Quarks



years of experimental discovery

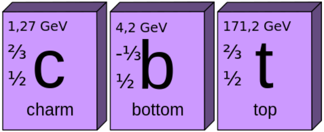
- 6 different quarks
- in 1974 only the three lightest were known

Quarks



years of experimental discovery

- 6 different quarks
- in 1974 only the three lightest were known
- focus on the charm, bottom and top quarks



Before 1974

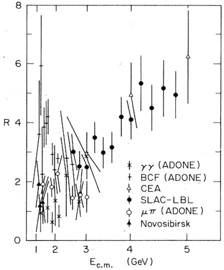
- first speculations by Bjorken and Glashow in 1964
- weak interaction description in the GIM mechanism (Glashow, Iliopoulos, Maiani) 1970 demanded hadron-lepton symmetry
- R-ratio measurements did not match theoretical predictions

$$R = \frac{\sigma_{\mathrm{e^+e^-\to hadrons}}}{\sigma_{e^+e^-\to\mu^+\mu^-}}$$

- theory predictions were

$$R = 3\sum_{i=u,d,s} q_i^2 = 2$$

- in experiment R-ratio grows with energy
- something is not understood



"Burton Richter - Nobel Lecture: From the Psi to Charm – The Experiments of 1975 and 1976". Nobelprize.org

November Revolution

Extraausgabe. Sonnabend, den 9. November 1918.

Vorwärts

Berliner Volksblatt.

Zentralorgan der sozialdemokratischen Partei Deutschlands.

Generalstreik!

Der Arbeiter- und Soldatenrat von Berlin hat den Generalstreik beschlossen. Alle Betriebe stehen still. Die notwendige Versorgung der Bevölkerung wird aufrecht erhalten.

Ein großer Teil der Garnison hat sich in geschlossenen Truppenkörpern mit Maschinengewehren und Geschützen dem Arbeiter- und Soldatenrat zur Verfügung gestellt.

Die Bewegung wird gemeinschaftlich geleitet von der Sozialdemokratischen Partei Deutschlands und der Unabhängigen sozialdemokratischen Partei Deutschlands.

Arbeiter, Soldaten, sorgt für Aufrechterhaltung der Ruhe und Ordnung.

Es lebe die soziale Republik!

Der Arbeiter- und Soldatenrat.

Location, Location, Location

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Stanford Linear Accelerator Center - SPEAR

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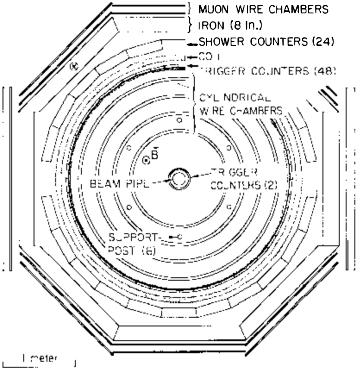
- Build in 1972
- radius $\sim$ 32 m
- electron - positron collider
- planned since 1964, but no funding
- building started 1970 out of operating budget of SLAC
- build on a parking lot without solid buildings
- first data in spring 1973

Picture: 1976

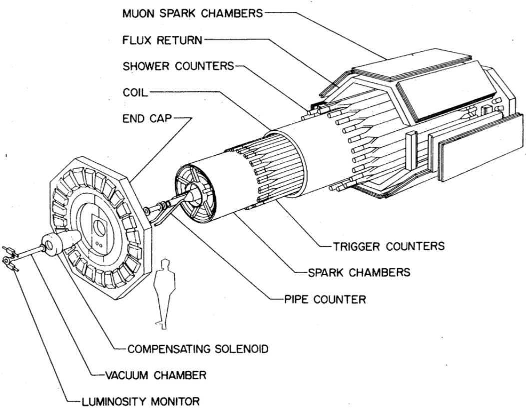
CERN Courier - The Ring in the Parking Lot

SLAC - Mark I Detector



Schwitters et al., Ann. Rev. Nucl. Sci. 26 (1976) 89

R.F



"Burton Richter - Nobel Lecture: From the Psi to Charm – The Experiments of 1975 and 1976". Nobelprize.org

Results from SPEAR

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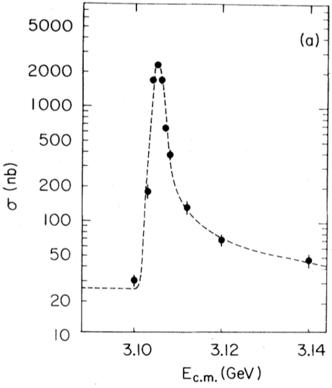

hadrons

- scanned the cross section in 200 MeV steps
- found clear enhancement at 3.2 GeV (6 nb)
- additional scan at 3.1 GeV was inconsistent
- fine scan showed clear peak just above $E_{c.m.} = 3.1$ GeV

J.J. Augustin et al. PRL 33 (1974) 1406

Brookhaven National Laboratory

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- Samuel Ting one of the first to learn about discovery at SLAC
- already measured at BNL, but confirmation was still in progress
- measurements at the Alternating Gradient Synchrotron (AGS)

"Samuel C.C. Ting - Nobel Lecture: The Discovery of the J Particle: A Personal Recollection". Nobelprize.org

Detector at BNL

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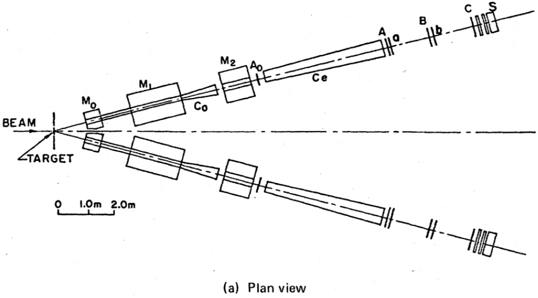
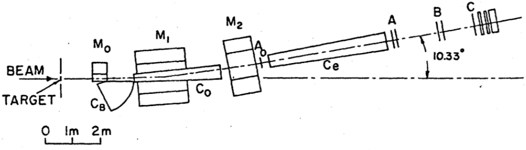


(a) Plan view



(b) Side view

- M_0, M_1, M_2: dipole magnets
- A_0, A, B, C: wire chambers
- a, b: hodoscopes
- S: shower counter
- C_0, C_e, C_B: Čerenkov counters

"Samuel C.C. Ting - Nobel Lecture: The Discovery of the J Particle: A Personal Recollection". Nobelprize.org

Results from BNL

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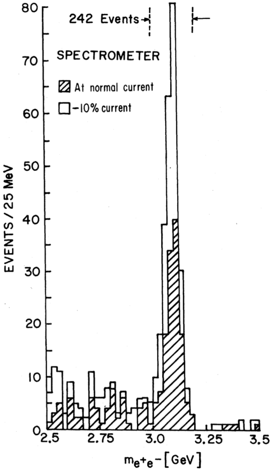
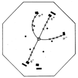


- protons on beryllium target at 24 GeV
- sharp peak at 3.1 GeV
- various tests to verify
  1. different currents for magnets
  2. two different programs for analysis
  3. varying target thickness

J.J. Auber et al. PRL 33 (1974) 1404

New particle J/ψ

- J for the looks of Tings name in chinese



- ψ from PSi $\leftrightarrow$ SPear and decay of ψ'
- new particle with mass $m = 3096.916 \pm 0.011$ MeV
- very narrow width ($\Gamma = 92.9 \pm 2.8$ keV)
  $\Rightarrow$ long lifetime
- quantum numbers $J^{PC} = 1^{--}$
- decay modes
  1. $J/\psi \rightarrow$ hadrons $\quad (87.7 \pm 0.5)\%$
  2. $J/\psi \rightarrow e^+e^- \quad (5.94 \pm 0.06)\%$
  3. $J/\psi \rightarrow \mu^+\mu^- \quad (5.93 \pm 0.06)\%$

Excitations in the ψ Spectrum

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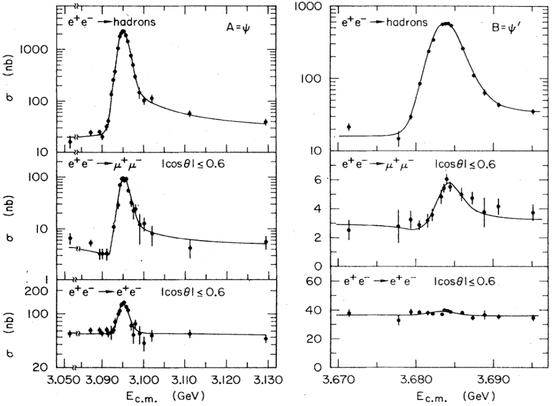
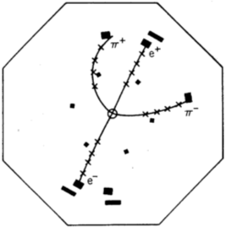


"Burton Richter - Nobel Lecture: From the Psi to Charm – The Experiments of 1975 and 1976". Nobelprize.org

$$\psi' \rightarrow J/\psi + \pi^+ + \pi^-$$
$$J/\psi \rightarrow e^+ + e^-$$

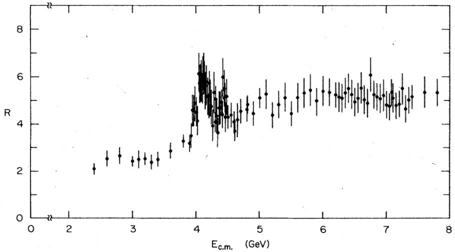


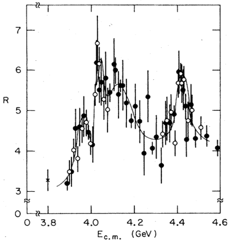
MARK I Event Dispay

Excitation ψ' was found 10 days after J/ψ

comparably narrow width

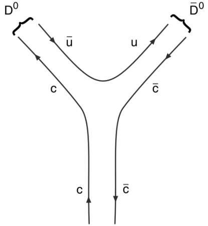
More Excitations





"Burton Richter - Nobel Lecture: From the Psi to Charm – The Experiments of 1975 and 1976". Nobelprize.org

- additional peaks were found
- much broader
  $\Rightarrow$ decay into lighter charmed mesons
- therefore $m_{\psi'}/2 < m_D < m_{\psi''}/2$
- $m_D \approx 1870$ MeV



Povh

Nobel Prize 1976

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Burton Richter and Samuel Ting were awarded the nobel prize of 1976

Almost Found Earlier

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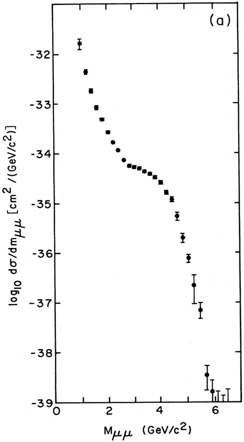

- results from 1973 at BNL
- group led by Leon Lederman
- reaction $p + U \rightarrow \mu^+ + \mu^-$

'The production cross section was seen to vary smoothly with mass exhibiting no resonant structure'

- very small signal to noise ratio

Phys. Rev. D8 (1973) 2016

Quarkonium

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Quarkonium consists of a quark q and its anti-quark $\bar{q}$

- For light quarks (u, d and s) not possible, flavor mixing
- For top quark not possible, decay time $(\approx 5 \cdot 10^{-25}$ s) is shorter than hadronization time
- only possible for charm and bottom quarks

charmonium and bottomonium

- analogous description to positronium

Positronium

Schrodinger equation:

$$\left(-\frac{\hbar^2}{2m}\Delta - \frac{\alpha\hbar c}{r}\right)\psi(\vec{r}) = E\psi(\vec{r})$$

with energy eigenstates and reduced mass

$$E_n = -\frac{\alpha^2 mc^2}{2n^2}, \qquad m = \frac{m_{e^-} m_{e^+}}{m_{e^-} + m_{e^+}} = \frac{m_e}{2}$$

width for 2 photon decay

$$\Gamma(1^1S_0 \to 2\gamma) = \frac{4\pi\alpha^2\hbar^3}{m_e^2 c}|\psi(0)|^2$$

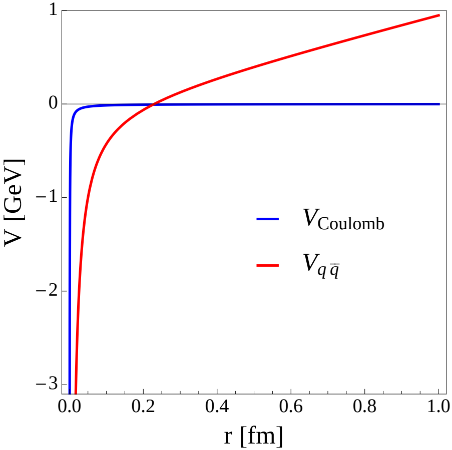
Charmonium

Modify potential

$$V_{q\bar{q}}(r, m) = -\frac{4}{3}\frac{\alpha_s(m)\hbar c}{r} + kr$$

$$k \approx 1\,\mathrm{GeV/fm}$$

$$\alpha_s(m_c = 1.5\,\mathrm{GeV/c^2}) \approx 0.2$$



Narrow width of J/ψ

- cannot decay into lighter charmed mesons $m(J/\psi) < 2m(D)$
- cannot decay into two gluons, because of charge parity conservation
- decay into three gluons suppressed α_s^3
  still 65% of partial width
- decay via virtual photon allowed
  35% partial width

Excitations in the ψ spectrum

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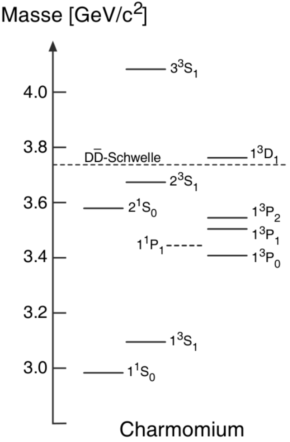

- additional splitting arises from spin-spin spin-orbit coupling

Povh

Bottom quark

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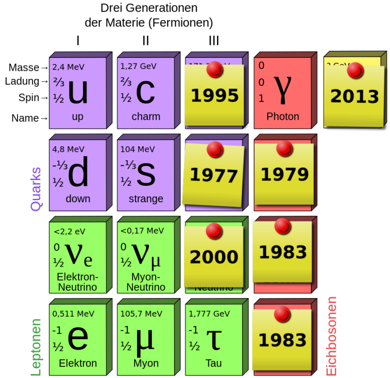

years of experimental discovery

- 1975 discovery of τ lepton hinted another quark family
- bottom quark was discovered at Fermilab 1977 by Lederman group

Detector at Fermilab

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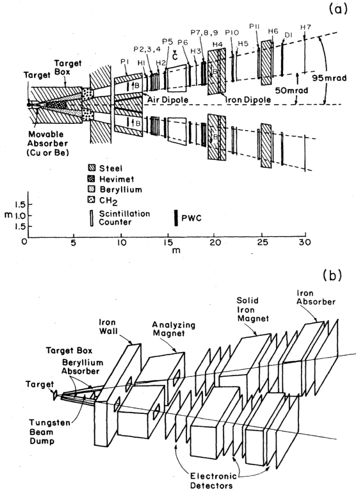
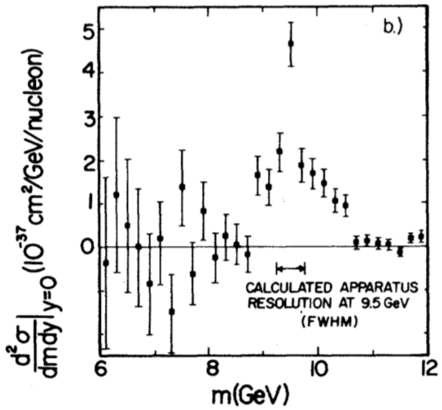


- $P1 - P11$: wire chambers
- $H1 - H7$: scintillation hodoscopes
- D: drift chamber
- $\check{C}$: Čerenkov counter

"Leon M. Lederman - Nobel Lecture: Observations in Particle Physics from Two Neutrinos to the Standard Model". Nobelprize.org

Results from Fermilab



- dimuon production cross section
- underground removed by exponential continuum fit
- new particle with mass $m = 9.44 \pm 0.03$ GeV
- the Υ meson ($b\bar{b}$)

S.W. Herb et al. PRL 39 (1977) 252

Properties of the $\Upsilon(1S)$ Meson

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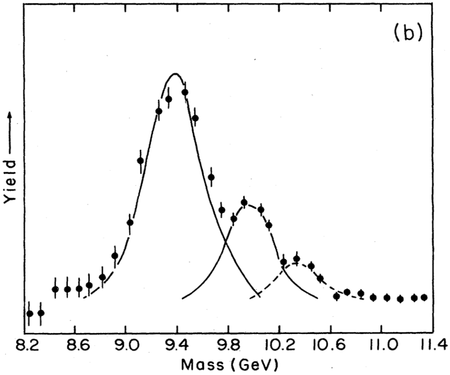
- mass $m = 9460.30 \pm 0.26$ MeV
- width $\Gamma = 54.02 \pm 1.25$ keV
- quantum numbers $J^{PC} = 1^{--}$
- decay modes
  1. $\Upsilon \to \tau^+\tau^-$ $(2.60 \pm 0.10)\%$
  2. $\Upsilon \to e^+e^-$ $(2.38 \pm 0.11)\%$
  3. $\Upsilon \to \mu^+\mu^-$ $(2.48 \pm 0.05)\%$
  4. $\Upsilon \to \gamma gg$ $(2.2 \pm 0.6)\%$
  5. $\Upsilon \to ggg$ $(81.7 \pm 0.7)\%$

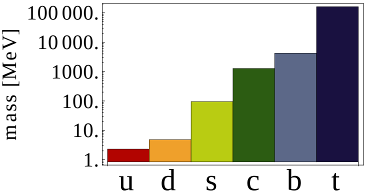
Υ Excitations



"Leon M. Lederman - Nobel Lecture: Observations in Particle Physics from Two Neutrinos to the Standard Model". Nobelprize.org

- excited states of Υ meson have been found
- $m_{\Upsilon(2S)} = 10.02326 \pm 0.00031$ MeV
  $\Gamma_{\Upsilon(2S)} = 31.98 \pm 2.63$ keV
- $m_{\Upsilon(3S)} = 10.3552 \pm 0.0005$ MeV
  $\Gamma_{\Upsilon(3S)} = 20.32 \pm 1.85$ keV

Top quark


100 000.
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mass [MeV]
u
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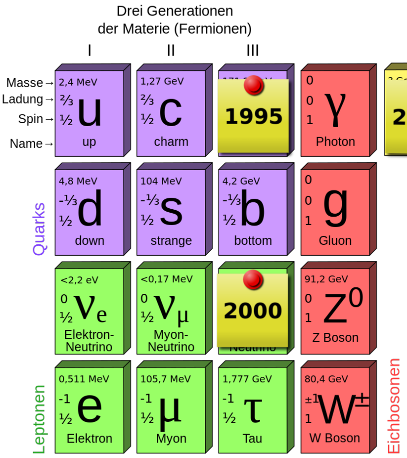
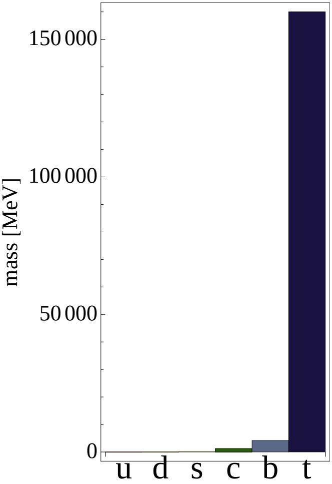

Drei Generationen
der Materie (Fermionen)
I
II
III
Masse→
Ladung→
Spin→
Name→
2,4 MeV ⅔ ½ u up
1,27 GeV ⅔ ½ c charm
1995
0 0 1 γ Photon
2013
4,8 MeV -⅓ ½ d down
104 MeV -⅓ ½ s strange
4,2 GeV -⅓ ½ b bottom
0 0 1 g Gluon
<2,2 eV 0 ½ νe Elektron-Neutrino
<0,17 MeV 0 ½ νμ Myon-Neutrino
2000
91,2 GeV 0 1 Z0 Z Boson
0,511 MeV -1 ½ e Elektron
105,7 MeV -1 ½ μ Myon
1,777 GeV -1 ½ τ Tau
80,4 GeV ±1 1 W± W Boson
Quarks
Leptonen
Eichbosonen

Top quark


150 000
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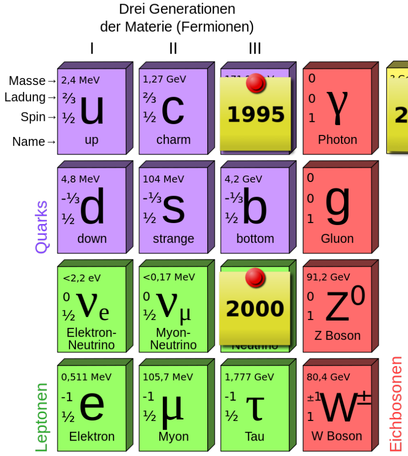
Drei Generationen
der Materie (Fermionen)
I
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2,4 MeV
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Elektron-
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Myon-
Neutrino
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0,511 MeV
-1
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Elektron
105,7 MeV
-1
½
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Myon
1,777 GeV
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τ
Tau
80,4 GeV
±1
1
W±
W Boson
Leptonen
Eichbosonen

Discovery of the Top Quark

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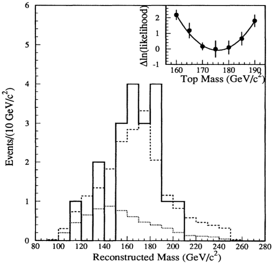
- due to high mass only Tevatron collider at Fermilab was able to produce it at the time (LHC reached same energy 2009)
- used $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV
- first evidence in 1994, officially published in 1995
- two experiments at Tevatron: Collider Detector at Fermilab (CDF) and DØ
- $t\bar{t}$ pairs produced and decay products ($t\bar{t} \rightarrow W^+ b W^- \bar{b}$) observed



F. Abe et al. PRL 74 (1995) 2626-2631