SULI Summer School 2018

Introduction to Flavor Physics

Bilas Pal

BROOKHAVEN NATIONAL LABORATORY

What is flavour physics?

WIKIPEDIA
The Free Encyclopedia

In particle physics, **flavour** or **flavor** refers to the *species* of an elementary particle. The Standard Model counts six flavours of quarks and six flavours of leptons. They are conventionally parameterized with *flavour quantum numbers* that are assigned to all subatomic particles. They can also be described by some of the family symmetries proposed for the quark-lepton generations.

Flavour in particle physics

Flavour quantum numbers

- Isospin: I or I_3
- Charm: C
- Strangeness: S
- Topness: T
- Bottomness: B'

Related quantum numbers

- Baryon number: B
- Lepton number: L
- Weak isospin: T or T_3
- Electric charge: Q
- X-charge: X

Combinations

- Hypercharge: Y
  - $Y = (B + S + C + B' + T)$
  - $Y = 2\,(Q - I_3)$
- Weak hypercharge: Y_W
  - $Y_W = 2\,(Q - T_3)$
  - $X + 2Y_W = 5\,(B - L)$

Flavour mixing

- CKM matrix
- PMNS matrix
- Flavour complementarity

v·t·e

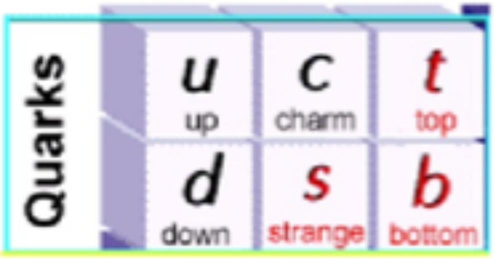
The term *flavor* was first used in particle physics in the context of the quark model of hadrons. It was coined in 1971 by Murray Gell-Mann and his student at the time, Harald Fritzsch, at a Baskin-Robbins ice-cream store in Pasadena. Just as ice cream has both color and flavor so do quarks (Fritzsch, 2008).

Review of Modern Physics 81 (2009) 1887

- The Standard Model is a kind of periodic table of the elements for particle physics.
- It can describe three of the four known fundamental forces (the electromagnetic, weak, and strong interactions, and not including the gravitational force) in the universe.
- The theory developed throughout the latter half of the 20th century, as collaborative effort of scientists around the world. The current formulation was finalized in the mid-1970s.
- It took actually 115 years to build the complete Standard Model. Physicist J. J. Thomson discovered the electron in 1897, and scientist at the LHC found the final piece of the puzzle, the Higgs boson, in 2012.

Standard Model of Particle Physics (continue)

elementary particles that feel strong force



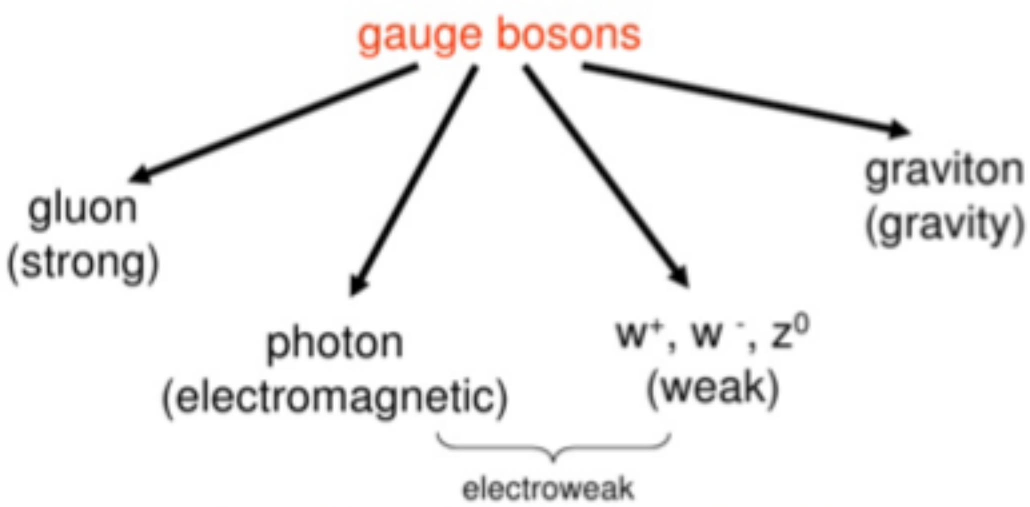
FERMIONS – follow Pauli exclusion principle

elementary particles that do not feel strong force

Gauge Bosons

DO NOT follow Pauli exclusion principle

Exchange Particles – Mediate Fundamental Forces



Range: gravity, electromagnetic >> strong > weak

Strength: strong > electromagnetic >> weak >> gravity

Mass: weak >>>> strong, gravity, electromagnetic

FERMIONS

Two types of fundamental particles are classified as FERMIONS (they follow Pauli's exclusion principle and have ½ spin numbers)

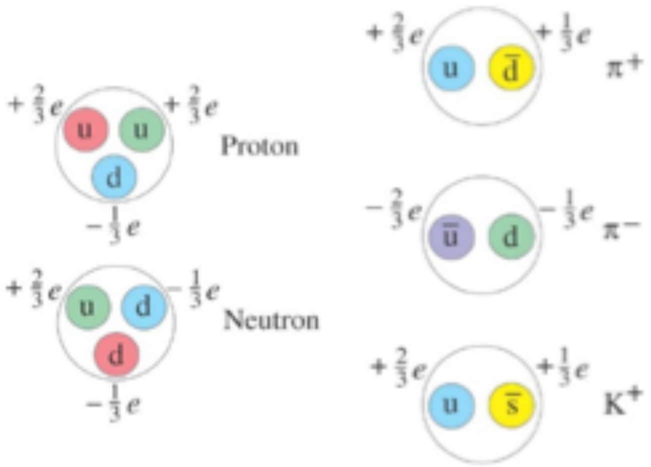
Present theory states that these particles cannot be broken down into even "smaller" particles.

These two classes of fundamental particles are.

Leptons – do not feel the strong force

Quarks – feel the strong force

Here are some examples of baryons and mesons.



Leptons

There are six types of lepton and each has an antiparticle (opposite charge).

Family	-1 charge	zero charge
1	electron (e)	electron-neutrino (υ_e)
2	muon (μ)	muon-neutrino (υ_μ)
3	tau (τ)	tau-neutrino (υ_τ)

Each lepton has a designated lepton number of +1. The antiparticles of each lepton are -1. For any interaction, the sum of all the lepton numbers must remain constant. This is the lepton number conservation law.

Quarks (isolated quarks have never been detected)

There are six types of quarks and consequently six types of anti-quarks (with opposite charge).

Family	+2/3 charge	-1/3 charge
1	up (u)	down (d)
2	charm (c)	strange (s)
3	top (t)	bottom (b)

Quarks and anti-quarks combine to form composite particles called HADRONS: two families of hadrons

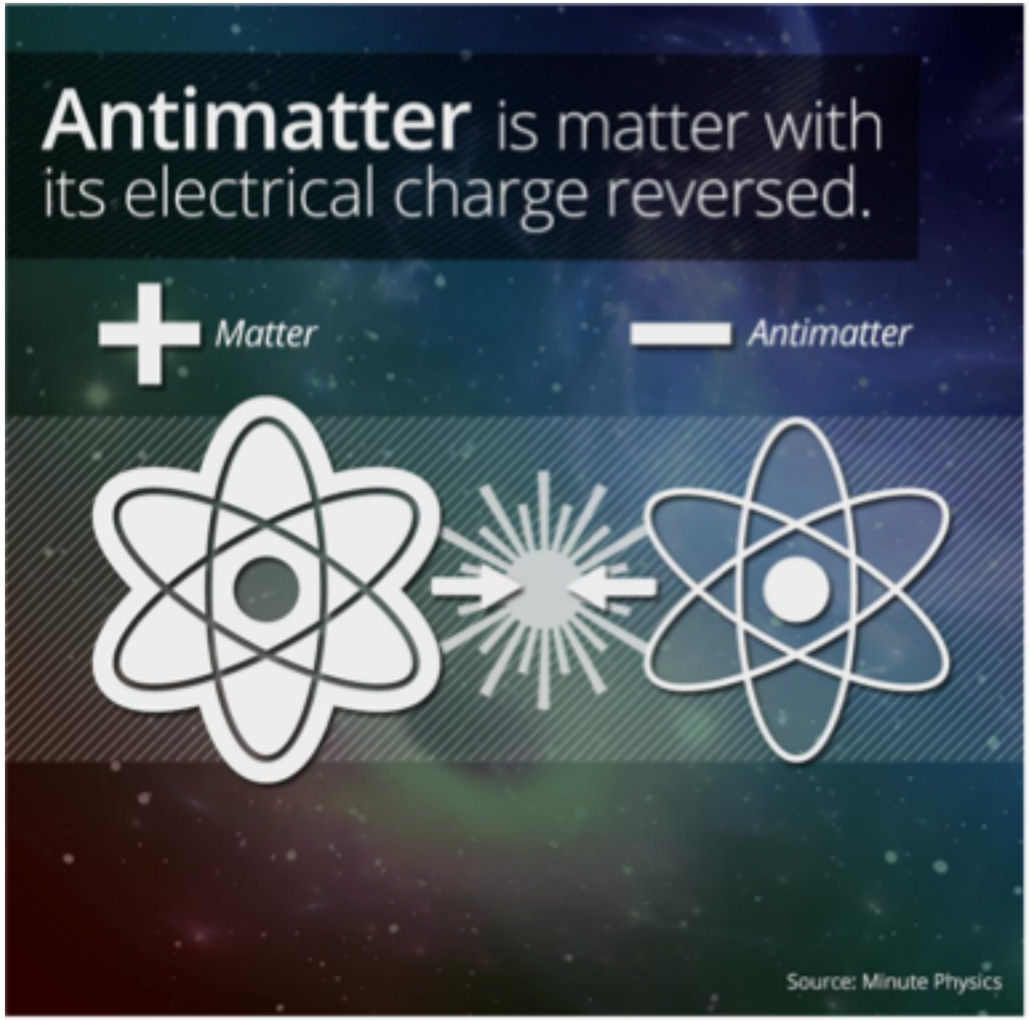
3 quarks = baryon (ex. protons and neutrons)

2 quarks = meson (ex. pions)

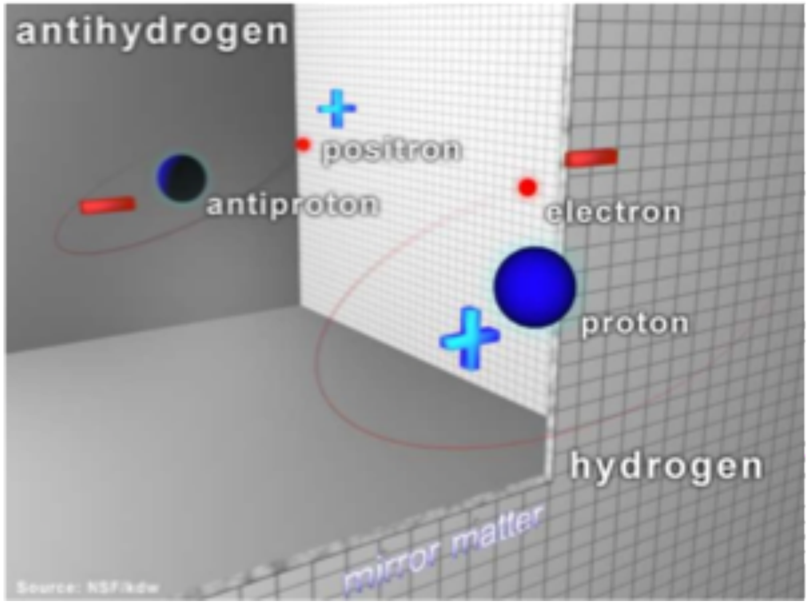
Mysteries of Flavor physics

- Why are there so many different fermions?
- What is responsible for their organisation into generations / families?
- Why are there 3 generations / families each of quarks and leptons?
- What causes matter–antimatter asymmetry?
- …

Antimatter?



An anti-electron (also called "positron") and an antiproton could form an antihydrogen atom in the same way that an electron and a proton form a normal hydrogen atom.

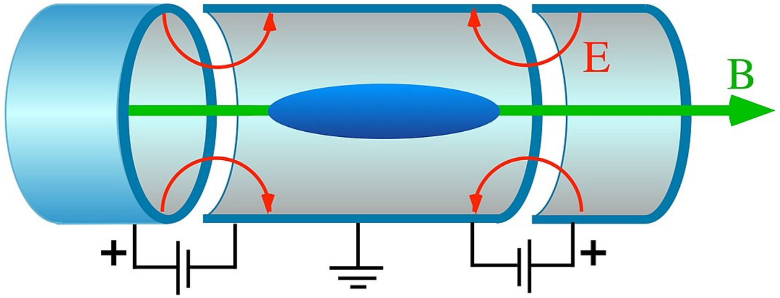


The modern theory of antimatter begins in 1928 with a paper by Paul Dirac. He realized his version of Schrodinger equation for electron was predicting the possibility of antielectrons. These antielectrons were latter discovered by Anderson in 1932 and named positrons.

Antimatter?

- Annihilation occurs when a subatomic particle collides with its respective antiparticle.
- Special device needs to store the antimatter.
- 1 gm of antimatter can produce twice as much energy as the bomb dropped on Hiroshima.
- However, It is too expensive. Roughly 100 billion dollar for 1 milligram of antimatter.
- With today's technology, antimatter is being considered for medical and rocket propulsion purposes.

Penning trap uses a homogeneous axial magnetic field and inhomogeneous quadrupole electric field.

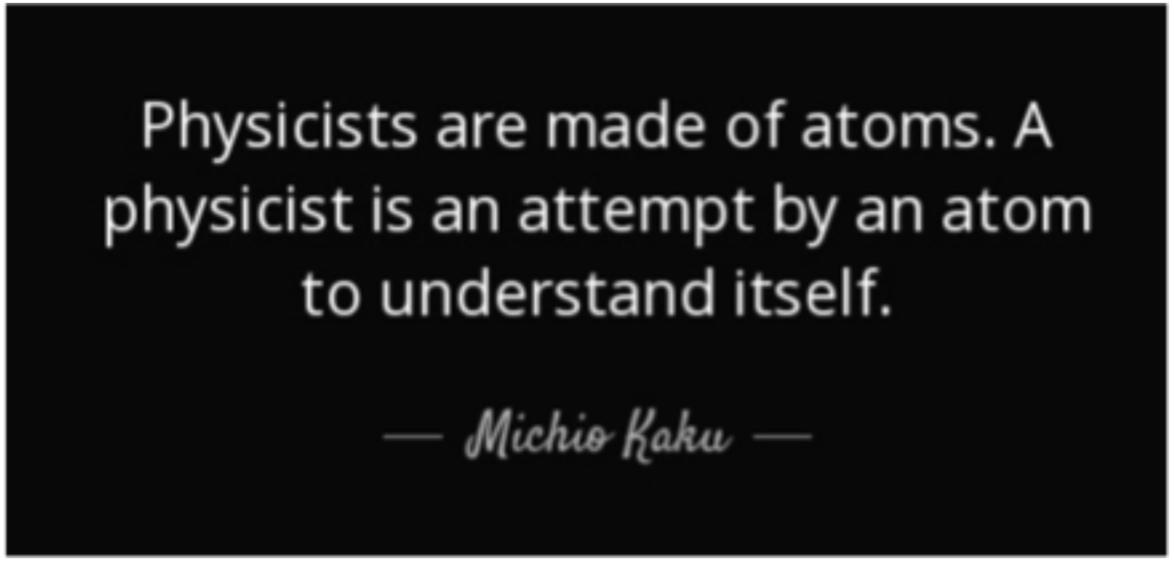


Matter-antimatter asymmetry

- During big bang matter and antimatter was created in equal proportion.
- But due to some unknown reasons matter overtook antimatter and what's left is mostly matter! (baryon asymmetry).
- This is one of the greatest unsolved problem in physics.

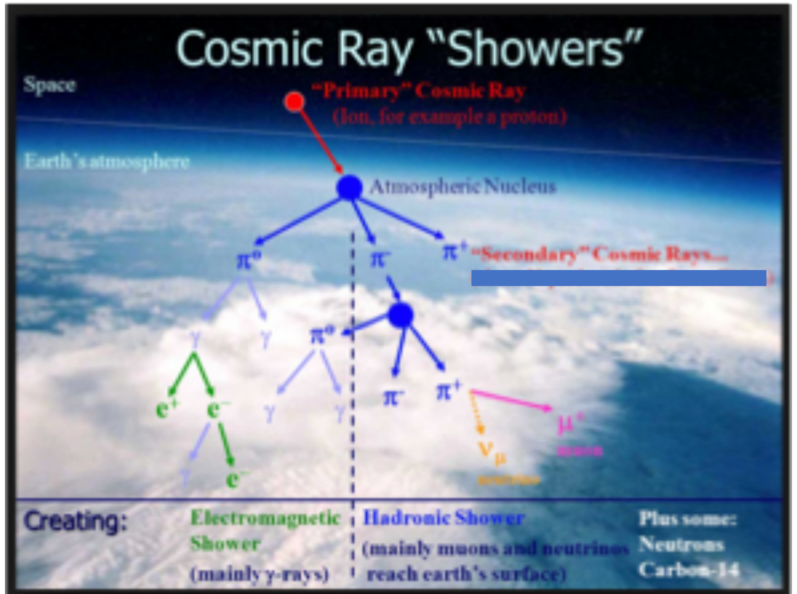
Why I do Flavor physics?

- To learn something about the mysteries.
- To search for New Physics beyond the Standard Model.



Early discoveries (before 1932)

- The first particle – electron has been discovered by J. J. Thomson at Cavendish Laboratory, Cambridge more than 100 years ago in 1897.
- Proton as constituent of nucleus was identified by Rutherford in 1919.
- Neutron has been discovered by Chadwick in 1932.

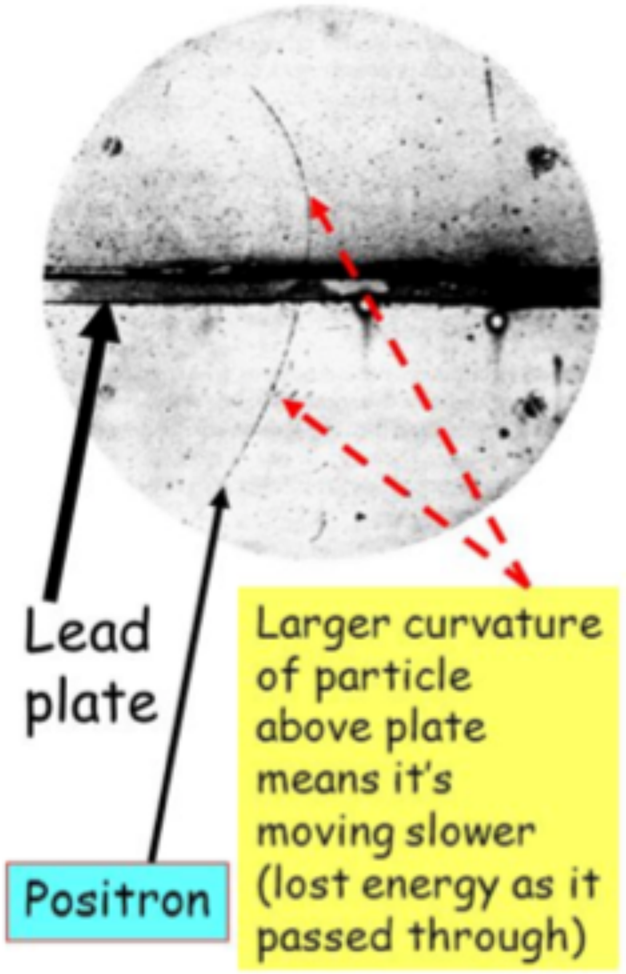


Cosmic Rays

- ❑ Cosmic Rays are energetic particles that impinge on our atmosphere (could be from sun or other faraway places in the Cosmos)
- ❑ They come from all directions.
- ❑ When these high energy particles strike atoms/molecules in our atmosphere, they produce a *spray* of particles.
- ❑ Many “exotic” particles can be created. As long as they are not so massive as to violate energy conservation they can be created.
- ❑ Some of these particles are unstable and “decay” quickly into other stable particles.
- ❑ Any of these exotic particles which live long enough to reach the surface of the earth can be detected !

Positron discovery in cosmic rays (1932)

Cloud Chamber Photograph



A "Cloud Chamber" is capable of detecting charged particles as they pass through it.

The chamber is surrounded by a magnet.

The magnet bends positively charged particles in one direction, and negatively charged particles in the other direction.

By examining the curvature above and below the lead plate, we can deduce:

(a) the particle is traveling upward in this photograph.

(b) it's charge is positive

Using other information about how far it traveled, it can be deduced it's not a proton.

It's a particle who's mass is same as electron but has positive charge → POSITRON!

This is the first evidence of antimatter.

That is, the positron has essentially all the same properties as an electron, except, it's charge is positive!

In 1936 Carl Anderson award Nobel prize for the discovery of the positron

Carl Anderson

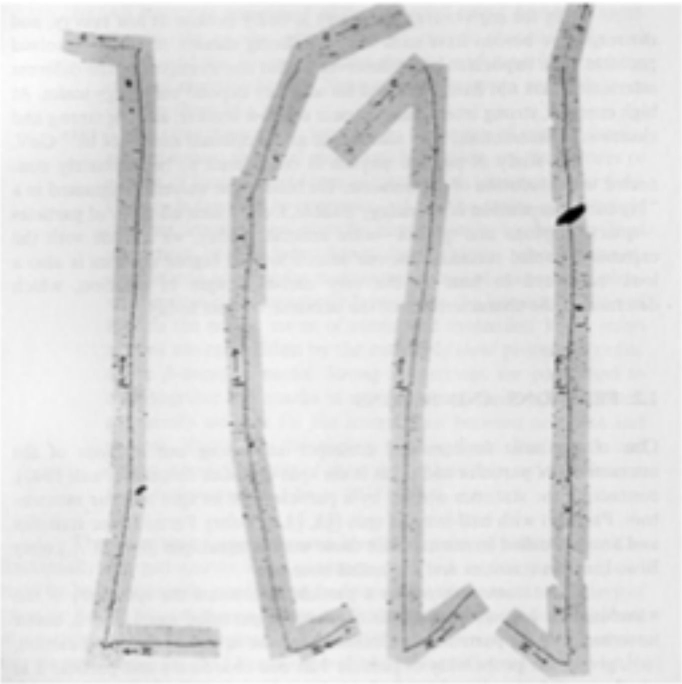
μ discovery

- Muons were discovered by Carl Anderson and Seth Neddermeyer in a cloud chamber experiment at Caltech in 1936.
- They noticed particles in the cosmic radiations that curved differently from electrons and other known particles when they passed through a magnetic field.
- The particles were positively and negatively charged and curved less sharply than electrons, but more sharply than protons for the same energy. To account for the difference in curvature, it was supposed that their mass was greater than that of an electron but smaller than that of proton.
- The observed feature can be explained if the particle has mass about 1/10 of the proton mass.
- It is unstable and decays in about $2\mu s$.
- Anderson initially called the new particle a mesotron; Greek “meso” means mid. It later become mu-meson and now muon.
- The existence of such particle was confirmed in 1937 by J. Street and and E. Stevenson.

Pion discovery

- Cecil Powell and colleagues at Bristol University used alternate types of detection devices to see charged tracks (called "emulsions") in the upper atmosphere.
- In 1947, they annouced the discovery of a particle called the π-meson or pion (π) for short.

Cecil Powell
1950 Nobel Prize winner



- Neutral pions do not leave tracks in photographic emulsions, and neither do they in cloud chambers. They were identified definitively at the University of California's cyclotron in 1950 by observing its decay into two photons.

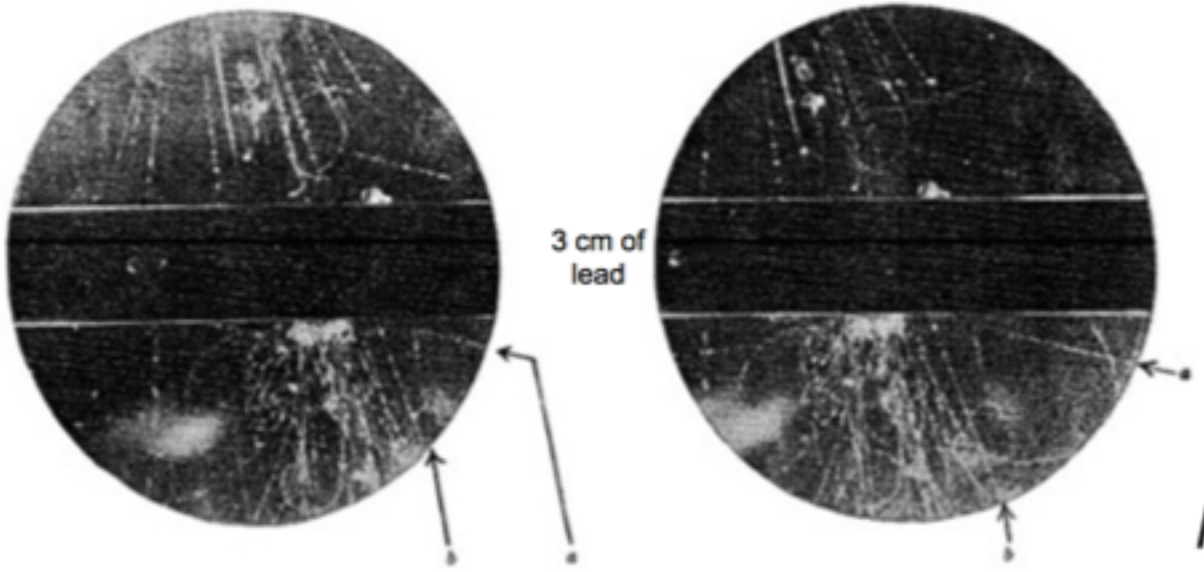
- Yukawa awarded the Nobel prize in 1949 for his prediction of Yukawa particle in 1935, which mediates nuclear interaction. The properties of pion was in agreement with the Yukawa theory prediction!

- Very unstable particles
  - For example, the π decays into a muon and an antineutrino with a mean lifetime of 2.6×10^{-8} s

Discovery of Strange flavor

N + p -> K+ K- X

- K meson (first in series of strange particle) have been discovered by the Manchester cosmic rays group (Rochester, Butler) in 1947.
- Decays of new particles have been observed in cloud chamber. Curvature and thickness of tracks observed showed that they corresponds to the nonrelativistic particle with mass in between pions and protons which were just like pions except for strangely long lifetime (decays to pions or a muon and neutrino)



- Neutral
- $m > 2m_\pi$
- "K^0"

$$K^0 \rightarrow \pi^+ + \pi^-$$

Some peculiar features are

- Always produced in pair
- They had lifetime of around 10^{-10}s, however they were produced in strong reactions, predicting particle lifetime of 10^{-23}s
- Decay weakly

The peculiar properties led to the new quantum number: strangeness.

- **Strangeness is conserved in strong and electromagnetic interactions**
- **Since K mesons are lightest strange particles, they can not decay with conservation of strangeness. Of course, heavier strange particle can decay via strong interaction with strangeness conservation.**

Introducing Quark

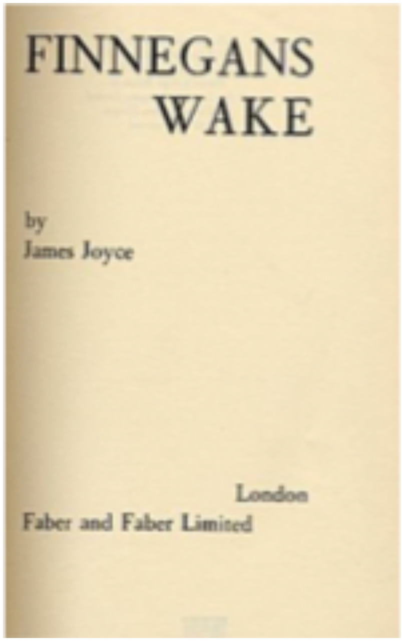
- In the three decades following 1932, the use of the higher and higher energies in particle detector led to the discovery of number of particles.
- In 1964, Murary Gell-Mann and George Zweig attempted to simplify the matter.
- They proposed that protons, neutrons and all the other hadrons were not as fundamental as once thought. Instead, they suggested that smaller particles called quarks are the true fundamental particles that make up hadrons.

Gell-Mann borrowed the word from *Finnegan's Wake* by James Joyce. At one point in the novel, a character, presumably drunk, exclaims

Three quarks for Muster Mark!

Murray Gell-Mann *George Zweig*

Gell-Mann received Nobel in 1969



Quarks

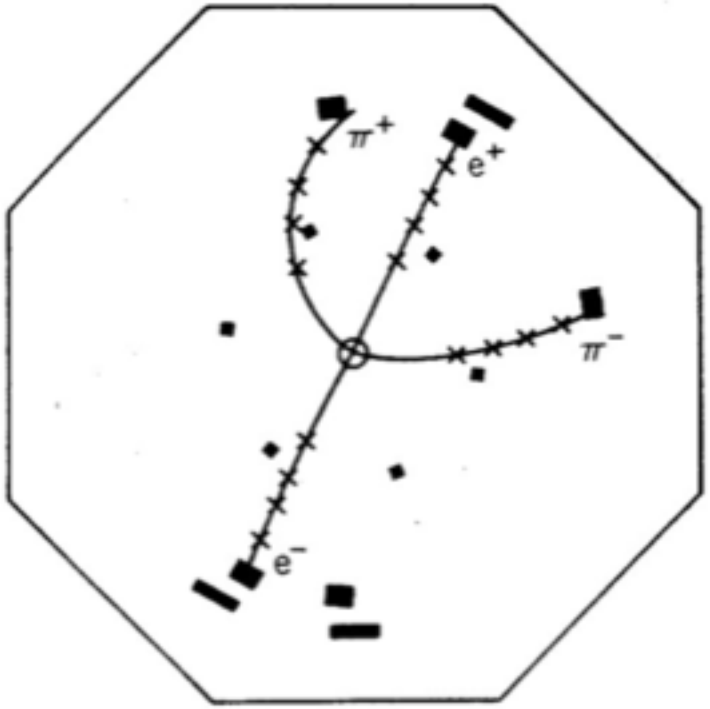
- Despite its stunning theoretical success, particle physicist were initially unwilling to accept the quark model.
- It was confirmed experimentally by deep inelastic scattering of electrons on protons and bound neutrons at SLAC in 1968.
- Jerome Friedman, Henry Kendall, Richard Taylor received Nobel in 1990.
- Friedman described their story "in which theory and experiment intermix".

VOLUME 23, NUMBER 16 PHYSICAL REVIEW LETTERS 20 OCTOBER 1969

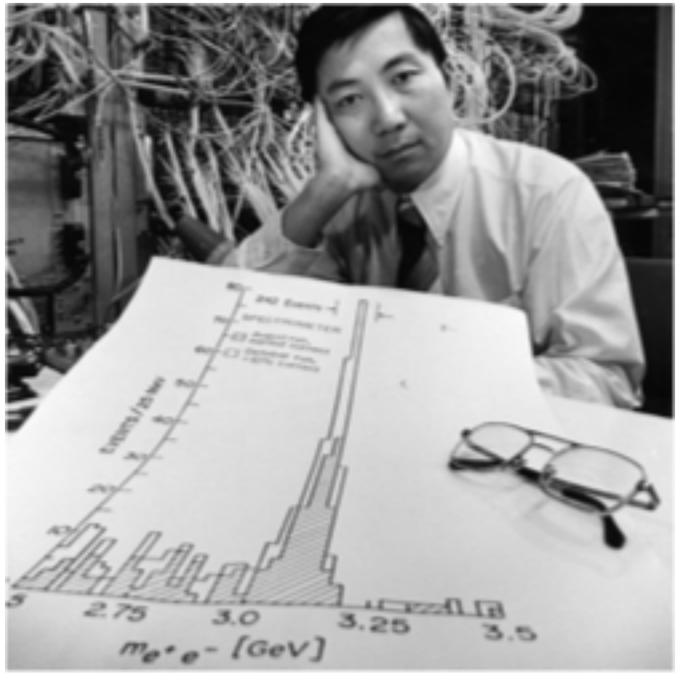
Discovery of Charm flavor

- It is associated with the discovery of J/ψ meson, identified as the composite of cc quarks. [Nov. 1974]
  - J : Samuel Ting, BNL
  - ψ : Burton Richter, SLAC

$$m(J/\psi) = 3.1\ \mathrm{GeV}$$
$$m(c) \sim 1.5\ \mathrm{GeV}$$



ψ discovery at SLAC



MIT Professor Samuel Ting at BNL

Richter and Ting shared the 1976 Nobel Prize in physics

Discovery of Charm flavor

2 Observations and 1 confirmation in the same issue of Physical Review Letter: Volume 33, Issue 23, December 2, 1974.

EDITORIAL

Publication of a New Discovery

This issue of Physical Review Letters must certainly be one of the most unusual in our history, with not just one but three extremely stimulating reports of a new discovery. Undoubtedly, the activity which will be aroused will be enormous and we happily join the rest of the physics community in congratulating those involved.

At the same time we would like to point out that the events of the past weeks placed some considerable stress not only on our office staff but also on our editorial policy regarding prior publication. We are grateful to the authors who were willing to meet our desires to defer publication announcements until the journal issue appeared. When, however, upon consulting our advisors we became aware of the truly unusual extent to which the entire high energy physics community was involved, we concurred that the news justified early public release. We hope that this decision will not be used as a precedent in future controversies concerning our stated editorial policies but will instead be taken as an indication that we are willing to bend these policies so as to be of service to the physics community.

J. A. Krumhansl

George L. Trigg

Discovery of Charm flavor

VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

Experimental Observation of a Heavy Particle J†

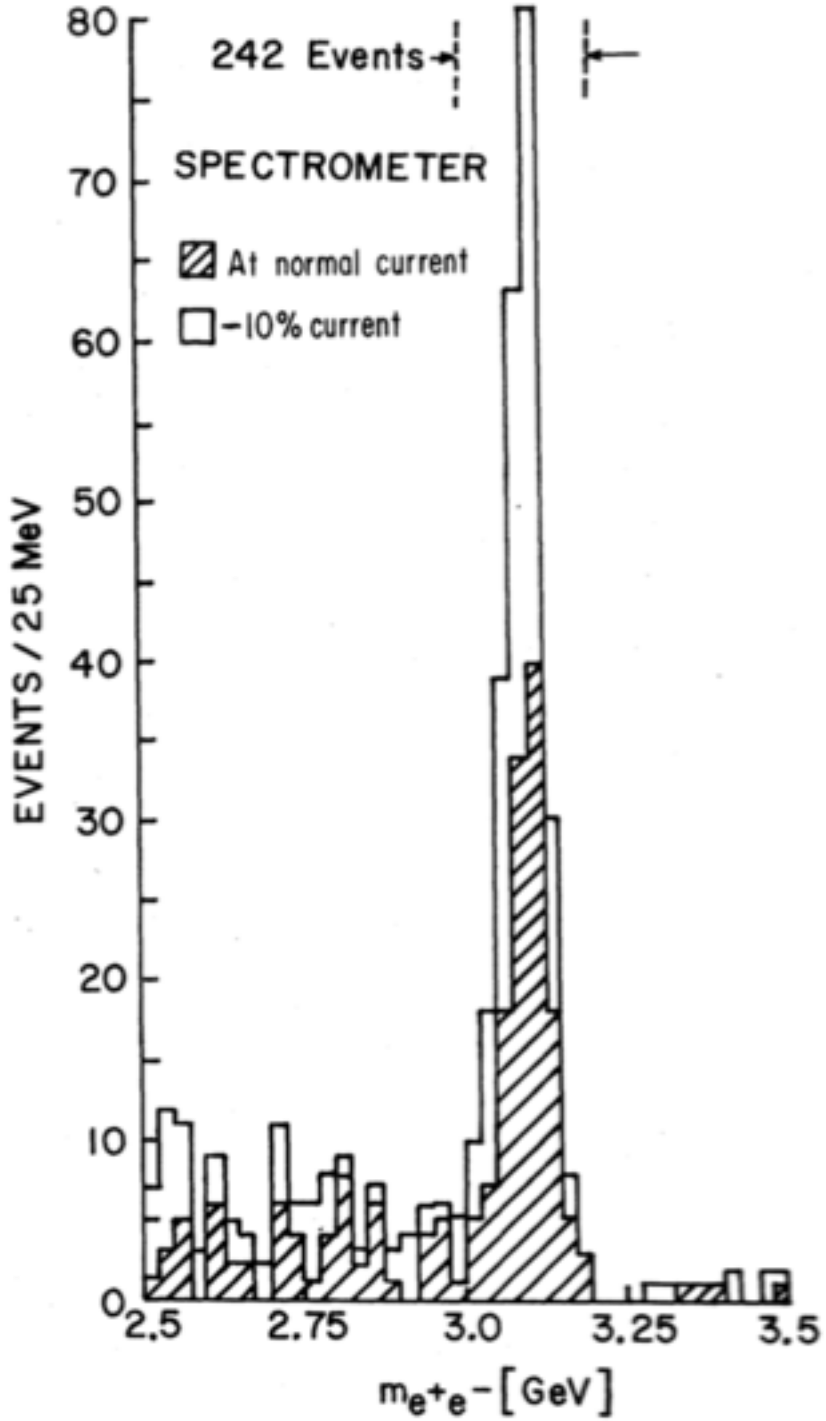
J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \mathrm{Be} \to e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

Discovery of Charmonium (J) at BNL: protons have been accelerated by BNL synchrotron up to 28.5 GeV and interacted with Beryllium target.
p + Be -> e+ e- X ; X represent the system of hadrons.



Discovery of Charm flavor

Discovery of a Narrow Resonance in e^+e^- Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

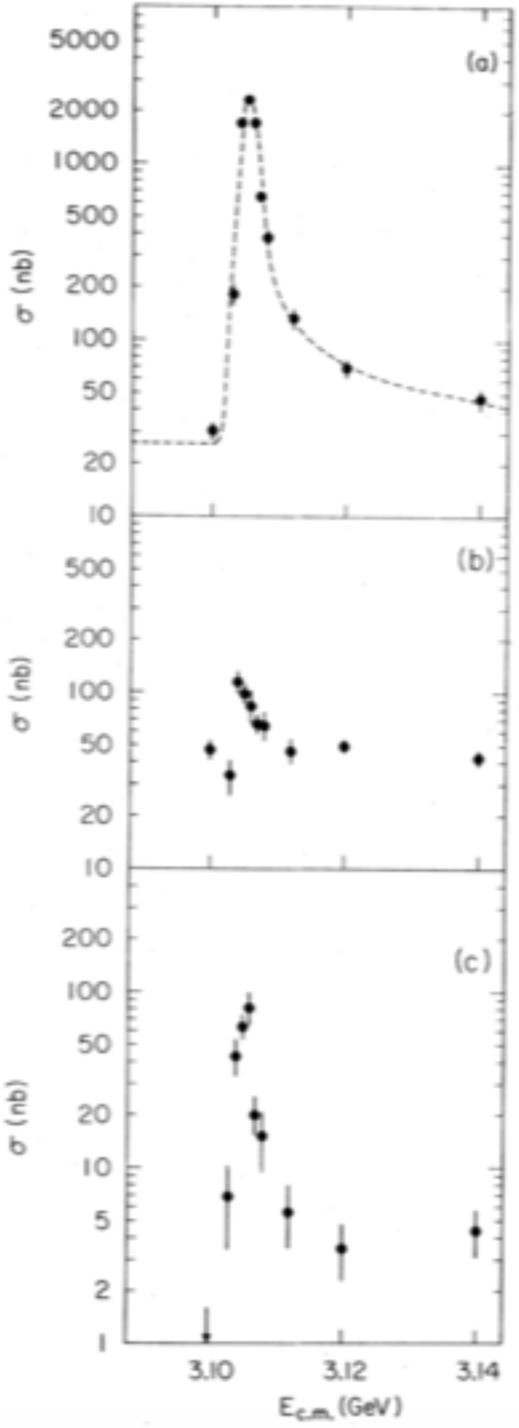
G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse

Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720

(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^- \rightarrow$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

Discovery of Charmonium (ψ) at SLAC: the annihilation of e^+e^- pair into hadrons, e^+e^- , $\mu^+\mu^-$. This is inverse process to that of S. Ting at BNL.



Confirmation of Charm flavor

Preliminary Result of Frascati (ADONE) on the Nature of a New 3.1-GeV Particle Produced in e^+e^- Annihilation*

C. Bacci, R. Balbini Celio, M. Berna-Rodini, G. Caton, R. Del Fabbro, M. Grilli, E. Iarocci, M. Locci, C. Mencuccini, G. P. Murtas, G. Penso, G. S. M. Spinetti, M. Spano, B. Stella, and V. Valente
The Gamma-Gamma Group, Laboratori Nazionali di Frascati, Frascati, Italy

and

B. Bartoli, D. Bisello, B. Esposito, F. Felicetti, P. Monacelli, M. Nigro, L. Paolufi, I. Peruzz G. Piano Mortemi, M. Piccolo, F. Ronga, F. Sebastiani, L. Trasatti, and F. Vanoli
The Magnet Experimental Group for ADONE, Laboratori Nazionali di Frascati, Frascati, Italy

and

G. Barbarino, G. Barbiellini, C. Bemporad, R. Biancastelli, F. Cevenini, M. Celvetti, F. Costantini, P. Lariccia, P. Parascandalo, E. Sassi, C. Spencer, L. Tortora, U. Troya, and S. Vitale
The Baryon-Antibaryon Group, Laboratori Nazionali di Frascati, Frascati, Italy
(Received 18 November 1974)

We report on the results at ADONE to study the properties of the newly found 3.1-BeV particle.

Confirmation of Charmonium (J/ψ) at Laboratori Nazionale di Frascati: the annihilation of e^+e^- pair into hadrons, e^+e^-, $\mu^+\mu^-$. Similar as SLAC experiment.

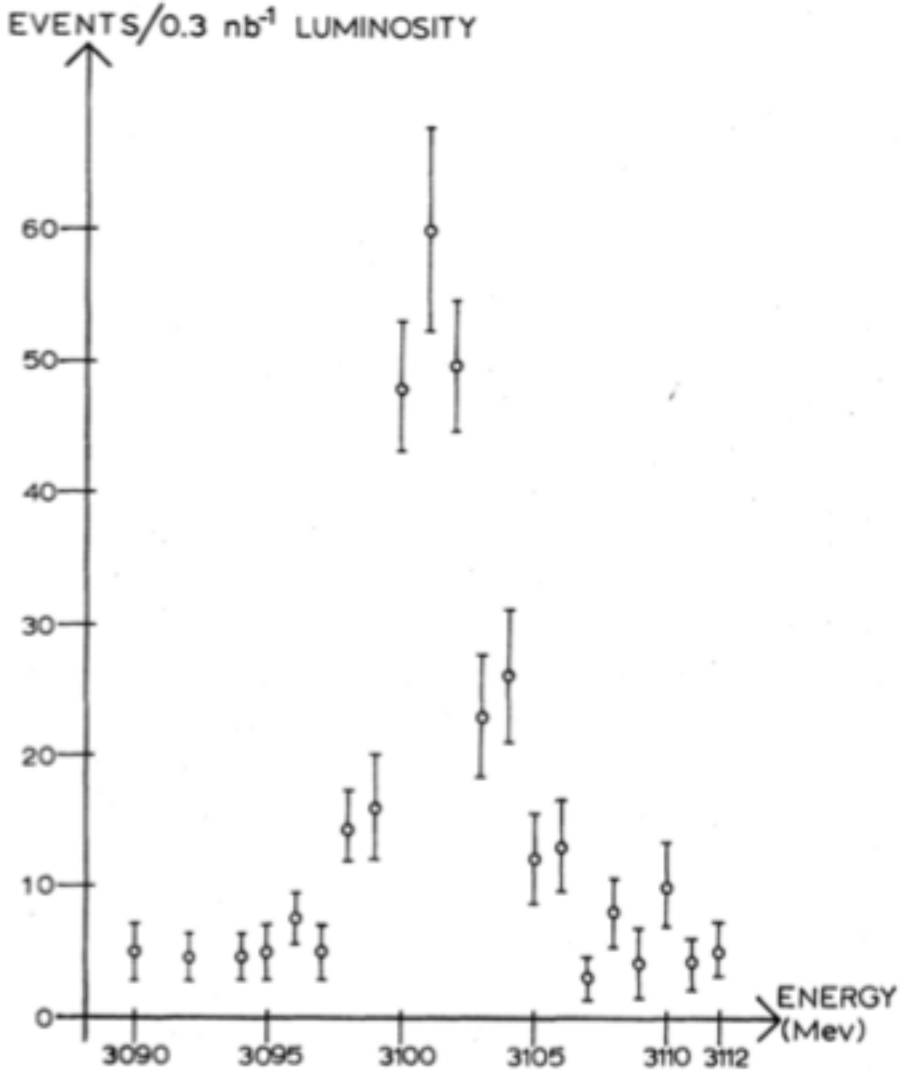


FIG. 1. Result from the Gamma-Gamma Group, total of 446 events. The number of events per 0.3 nb^{-1} luminosity is plotted versus the total c.m. energy of the machine.

τ lepton discovery

Martin Perl

- In 1975, in SLAC Martin Perl and collaboration used the same machine as was used for J/ψ. They have studied production of leptons in e+e- annihilation.

Physical Review Letters V35, Issue 22, page 1489

We have found 64 events of the form

$$e^+ + e^- \to e^\pm + \mu^\mp + \geq 2 \text{ undetected particles} \quad (1)$$

for which we have no conventional explanation.

This events have the following properties

- Energy and momentum loss
- Apparent violation of lepton flavors
- The events appear above certain threshold energy > 3.6 GeV

We conclude that the signature e-μ events cannot be explained either by the production and decay of any presently known particles or as coming from any of the well-understood interactions which can conventionally lead to an e and a μ in the final state. A possible explanation for these events is the production and decay of a pair of new particles, each having a mass in the range of 1.6 to 2.0 GeV/c^2.

The new particle pair is $\tau^+\tau^-$. Greek τ is third in English; τ is the third charged lepton discovered.

20 years later, Perl awarded the Noble Prize in 1995 for this discovery together with the discovery of neutrino with Frederick Reines.

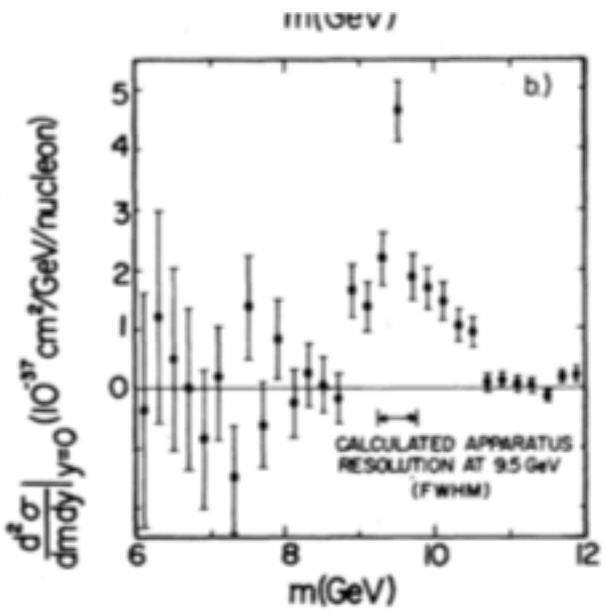
Discovery of Beauty/Bottom flavor

- Bottom quark has been introduced theoretically in 1973 by Kobayashi and Masakawa in attempts to explain the matter-antimatter asymmetry in Standard Model.
- The discovery of b-quark was similar to the discovery of the c-quark.
- In 1977 the Υ mesons have been observed at Fermilab and interpreted as the composite state of bb quarks.
- Each quark has the same mass $\sim 4.5\ GeV$ and the mass Υ meson is about double of the b-quark mass.

Leon Lederman, who is also famous for his book ”The God Particle” published in 1993

The proton beam had the energy about 400 GeV. Instead of electrons and positrons, muons were detected . p + Be -> + $\mu^+\mu^-$ X ; X represent the system of hadrons.

In 1978 Υ has been discovered also in e+ e- channel by measuring the total cross-section.



Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions

S. W. Herb, D. C. Hom, L. M. Lederman, J. C. Sens,[a] H. D. Snyder, and J. K. Yoh
Columbia University, New York, New York 10027

and

J. A. Appel, B. C. Brown, C. N. Brown, W. R. Innes, K. Ueno, and T. Yamanouchi
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

A. S. Ito, H. Jöstlein, D. M. Kaplan, and R. D. Kephart
State University of New York at Stony Brook, Stony Brook, New York 11974

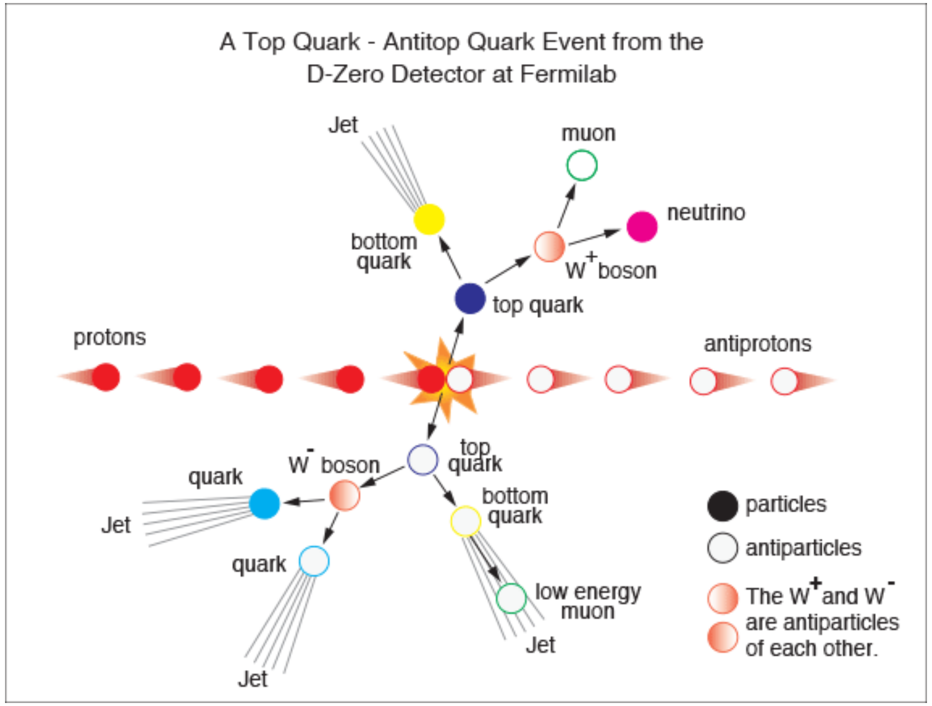
(Received 1 July 1977)

Accepted without review at the request of Edwin L. Goldwasser under policy announced 26 April 1976

Dimuon production is studied in 400-GeV proton-nucleus collisions. A strong enhancement is observed at 9.5 GeV mass in a sample of 9000 dimuon events with a mass $m_{\mu^+\mu^-}$ > 5 GeV.

Top quark discovery

- The history of the top was dramatic. After b-quark discovery it was clear that the top quark should exists. Predictions of mass of this quark changed many times being 20, 40, 60, 100, 180 GeV.
- Discovered at Fermilab (CDF and D0 at Tevatron) in 1995.
- CDF found 37 top candidate events (12 background events), D0 found 17 top candidate events (4 background events).
- $m{\sim}172\ GeV$.
- Single Top first produced in 2006 at D0.
- The top quark has its own phenomenology; it does not hadronize.



Although top is one of the quark flavor, it is studied separately under “TOP Physics” not under “Flavor Physics”.

Flavor physics experiment

Flavor Physics experiments (not the full list)

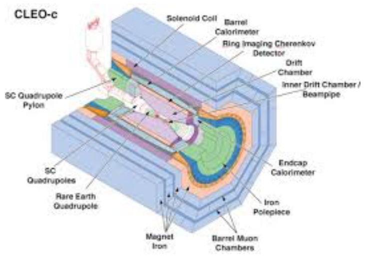
BaBar at SLAC

D0 and CDF at FermiLab

ATLAS, CMS, LHCb and ALICE at CERN (Europe)

Belle at KEKB (JAPAN)

BESIII at Beijing (China)



CLEO at Cornell

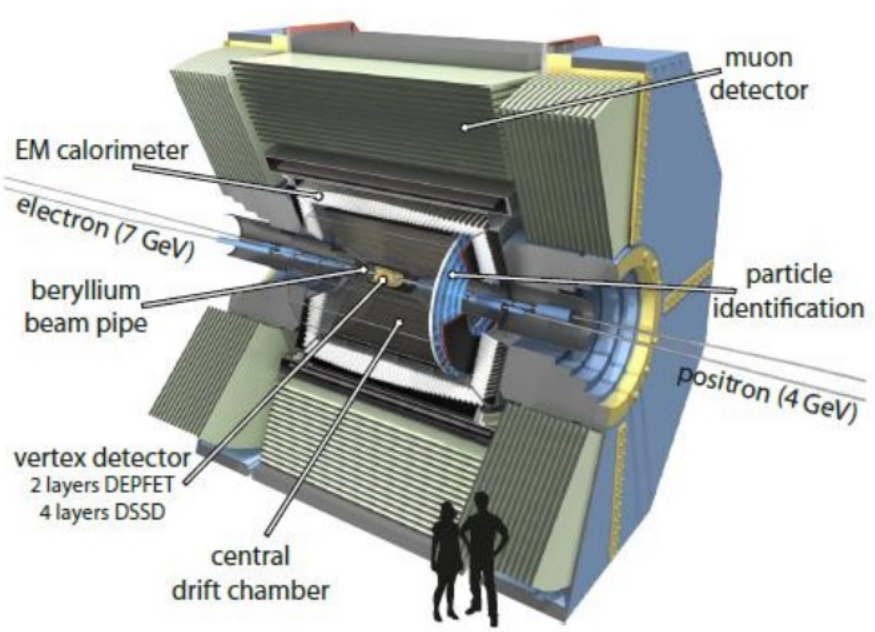
STAR and PHENIX at RHIC (BNL)

Neutrino experiments are not mentioned here.

Belle II experiment

- Belle means beauty; the main purpose of the Belle experiment is to study the properties of B mesons (heavy mesons containing a beauty/bottom quark).
- Belle II is the successor to the Belle experiment, aim is to take 50 times more data than Belle.
- It is an international collaboration hosted by KEK in Tsukuba, Japan.
- Using the same old KEK tunnel, but most of the parts are new.
- Electron and positron beams travelling close to the speed of light with 7 GeV and 4 GeV, respectively collide in KEK.
- Data taking started without a central subdetector: this is to understand the background, calibration etc. Early next year, we plan to take data with all the subdetectors installed.
- BNL is responsible for Computing and Physics analysis
- 16 BNL members

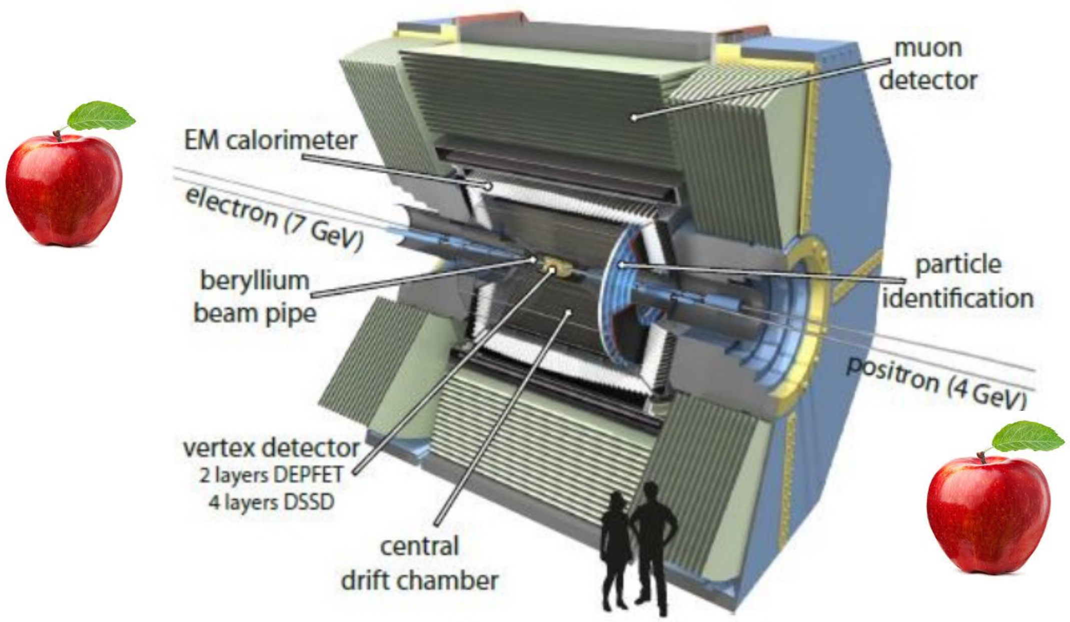
Belle II experiment



How powerful Belle II collision is?

- An electron volt (eV) is a unit of energy, like a calorie or a joule. We use eV for the energy of motion of really small things, such as particles/atoms.
- One photon of infrared light (longer wavelength than the visible light) has about 1 eV of energy. A flying mosquito has about 4 TeV of energy.
- 7+4 = 11 GeV is ~350 times lower than the energy of a flying mosquito.
- But remember that, an electron or a positron is 1000 trillion times smaller than a mosquito.
- Nowhere else on Earth can we concentrate energy that much.

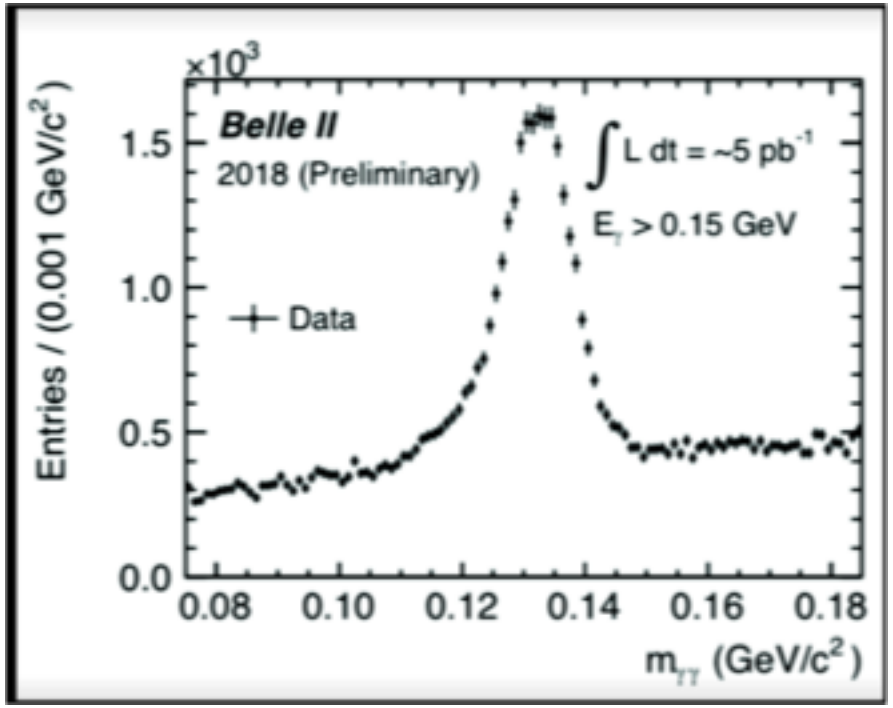
Belle II experiment



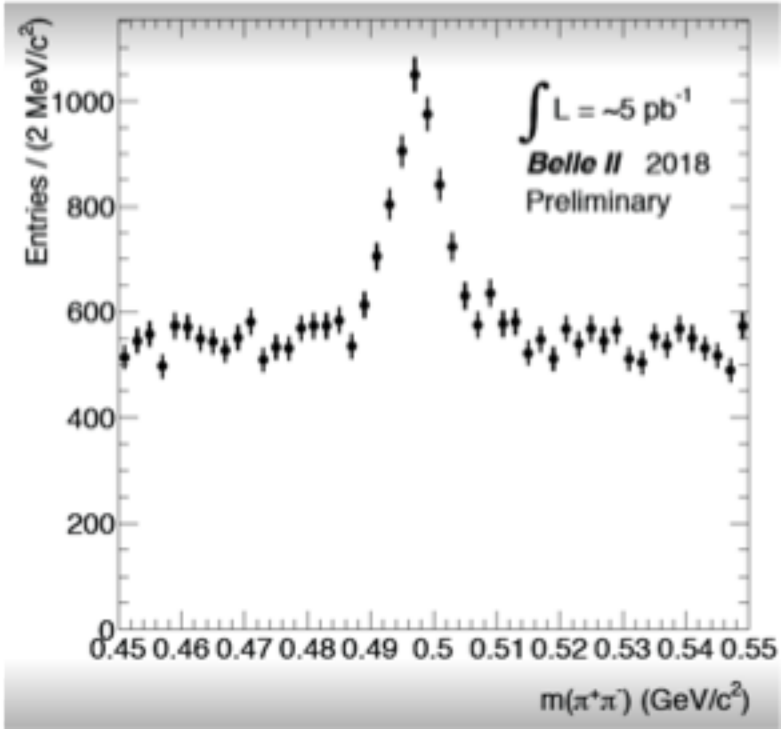
What happened if we collide two apple instead of electron and positron?

- We get a special juice with huge energy.
- This energy is close to 10^20 Joule.
- This is approximately same amount of energy that was released when a 1.2 miles diameter space object (either an asteroid or a comet) hit Canada 39 million years ago. The impact of that collision resulted in the Haughton Crater, which is about 14 miles across.
- In reality, we can not accelerate two apples in Belle II.

Rediscoveries from brand new Belle II



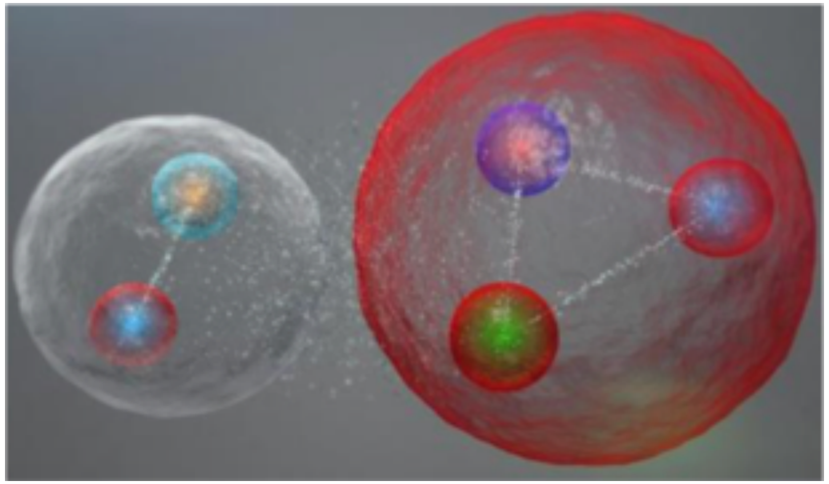
Neutral pion rediscovery



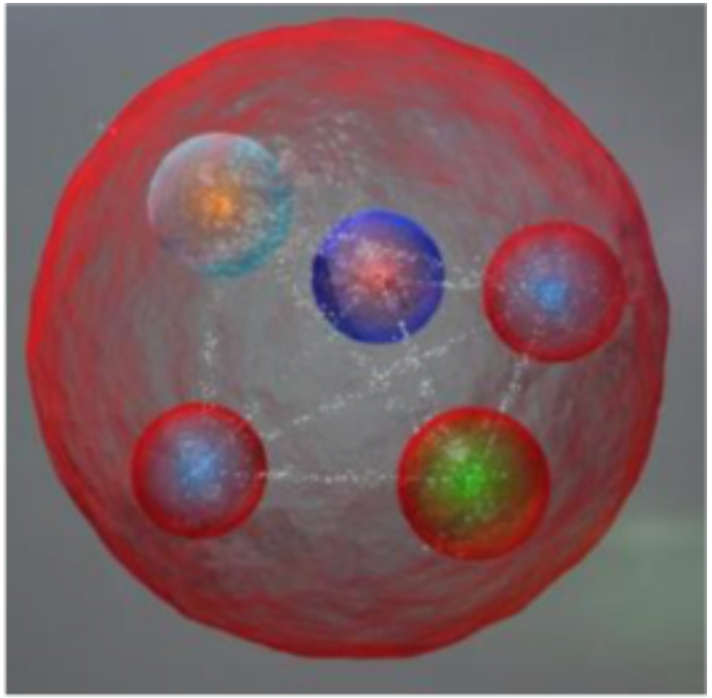
Neutral kaon rediscovery

Some experimental results

Pentaquark



- A pentaquark, as the name suggests, is made up of five quarks. The existence of pentaquarks was theorized half a century ago in 1960s by Murray Gell-Mann.
- Pentaquarks have been reported several times in the past, but they all appeared to be fakes.
- In 2015, two pentaquarks were discovered at CERN's LHCb experiment, but accidently.



HUFFPOST

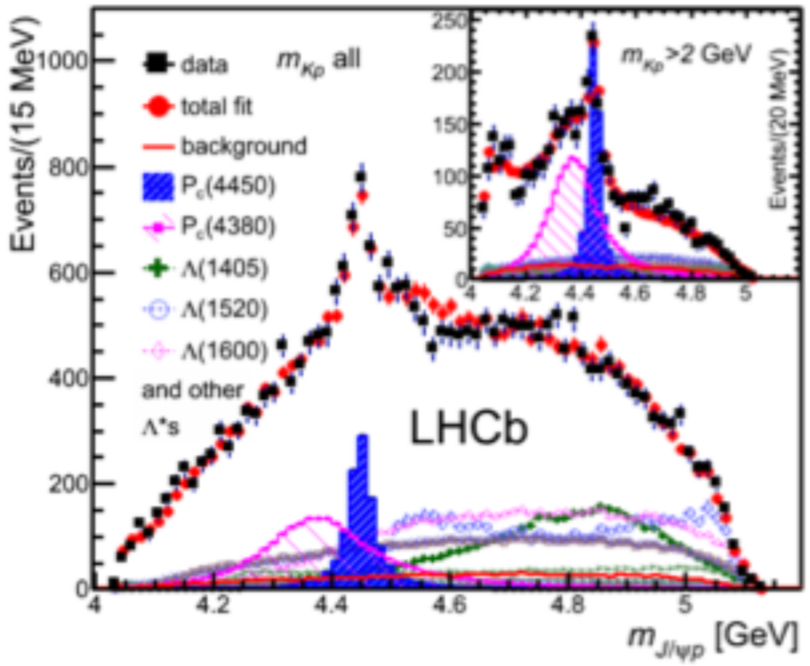
Pentaquarks: A New State of Matter

By Sheldon Stone

~~much heavier than the light quarks that make up the proton~~. We were looking for decays of a particle called a B meson into a J/ψ and two other particles.

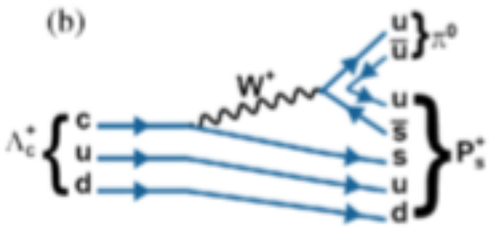
One of our colleagues suggested that a particular background was possible that could fake our signal from the decay of a baryon called the Λb which contains a b-quark, a u-quark and a d-quark, compared with the proton which contains two u-quarks and a d-quark. The background process had the Λb decaying into a J/ψ plus a proton and a negatively charged kaon. This decay had never been seen before. The graduate student who was working on the B meson decay for his thesis was asked to look for the background and he begrudgingly went off and did it. He returned with a smile. He had found a very large signal. It was immediately used to measure the Λb lifetime which had be an outstanding issue for twenty years (unstable particles have lifetimes, they decay after a certain mean time just like radioactive nuclei). Previous measurements had disagreed with the theoretical prediction, but out data showed that the prediction was correct. There was, however, one feature of the data that surprised us; while most of the decay looked like what we expected, about 10% showed a bump in the J/ψ p mass. If real this would have to be the decay of a pentaquark.

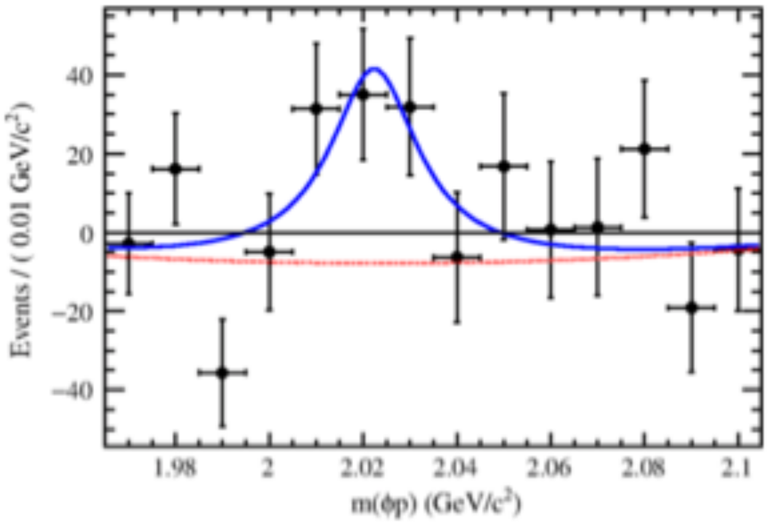
Pentaquarks



R. Aaij *et al.* (LHCb Collaboration)
Phys. Rev. Lett. **115**, 072001 – Published 12 August 2015

"Our experiment is beautifully designed for understanding these sorts of things," says Wilkinson. "We have the perfect microscope for looking more closely. This will certainly not be the last pentaquark discovered."





Belle experiments search for pentaquark in Lambda_c decays. But no significant signal is found.

B. Pal *et al.* (Belle Collaboration)
Phys. Rev. D **96**, 051102(R) – Published 22 September 2017

Many searches ongoing.

Many contents are taken from www.
Apologies not to cite them properly.