# Particle Accelerators & Detectors

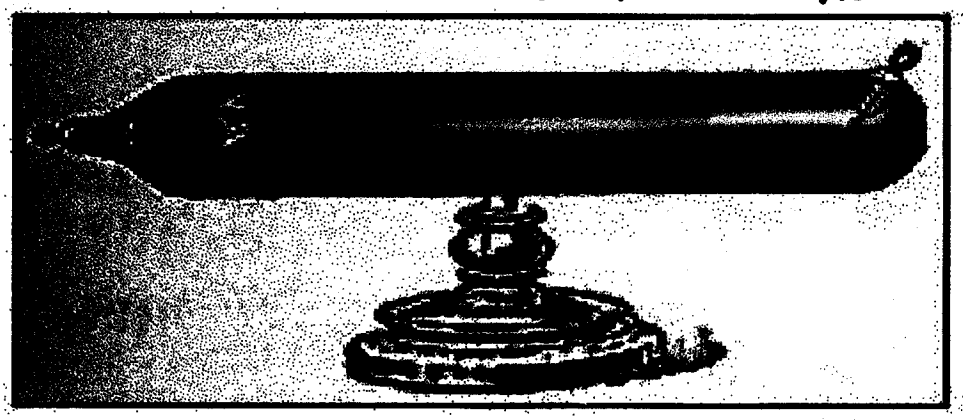
## Tools of Discovery in ~~HEP~~

Faraday had found (in mid-1800's) that if he evacuated a glass tube, inserted sealed electrodes at either end and applied high voltage across, a glow appeared!

With improvements in vacuum, more interesting phenomena were observed.

- bending of the glow near a magnet (Plucker, 1858)
- the radiation was emanating from the negative electrode → "Cathode Rays"

The Earliest Accelerator: The "Glow Tube"

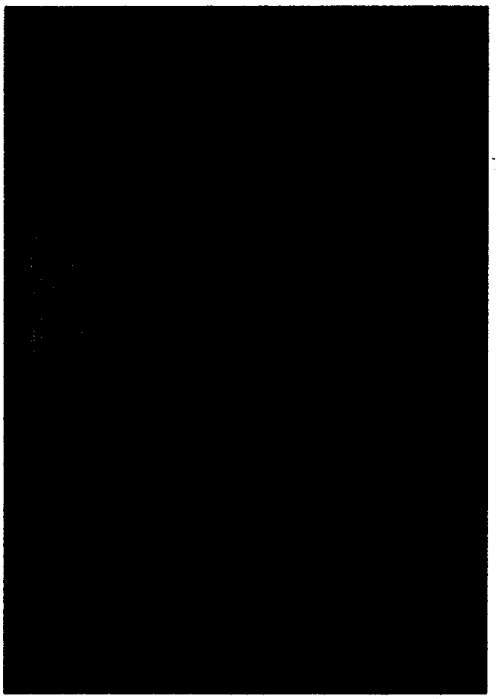


Speculations that the emanations were waves (Hertz)
electrically charged particles (Crooke, Perrin)

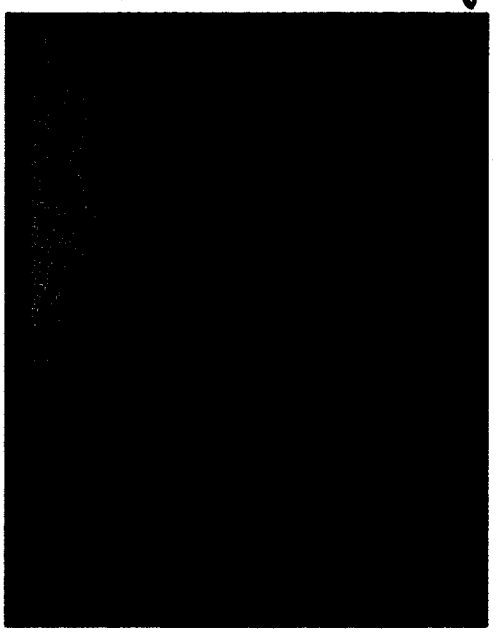
# The "Ghost Rays" from the "Glow Tube"

November 1895:
Rontgen working with the Glow Tube saw fluorescing of a sheet treated with Barium Platinum Cyanide

→ X-rays
→ Sends out preprints of findings on Jan. 1, 1896
→ Causes a sensation, a flurry of activities, a plethora of new reports
1,000 papers on X-rays within a year
→ Nobel Prize in 1901



William Konrad Röntgen, Wurzburg, Germany



Rontgen's wife's hand with ring

# Discovery of The Neutrino

James Chadwick measures a continuous energy spectrum in $\beta$-decay

- Radium used as source
- ion counter as detector
- measures magnetic deflections

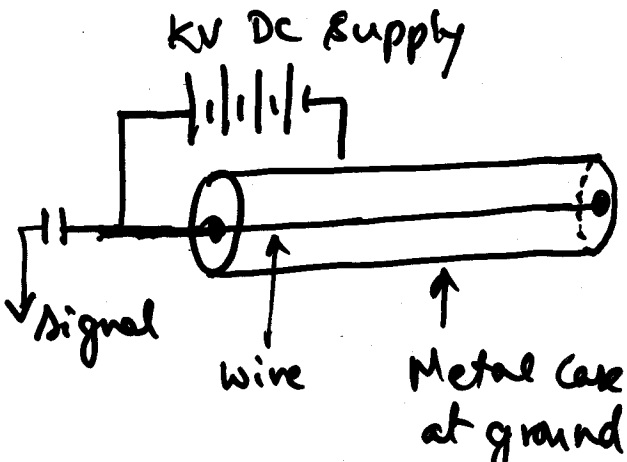
Ellis uses a large cylinder of Pb as a <u>Calorimeter</u> equipped with a thermocouple

In 1930, Pauli suggests "neutrino" to explain the lost energy and the Continuous spectrum.

- More sophisticated detectors came before sophisticated accelerators

**Cloud chamber:** Invented by C. T. R. Wilson in 1894, But, only in 1910, Wilson saw charged particle tracks
- Served as the workhorse for Nuclear & Particle Physics until the advent of Bubble chamber (1960's)

**Geiger Counter:** First gas ionization counter detector
Invented in Rutherford's lab in 1910.
Got widely used in cosmic ray research as inexpensive & rugged detector of radiation




typically 10" long, 1" dia

All these discoveries were made using the glow tube electron accelerator or natural radioactivity

+

Fluorescent screens, photographic films, human eyes as detectors

The Cathode Ray Tube could be upgraded to step up the electron energy to several hundred kilovolts. But, it was desirable to compete with the energies of MeV range $\alpha$-particles.

The new realm of matter, the atom and its innards, needed more powerful accelerators and detectors, for further explorations

# Rutherford Scattering
## A Historical Proto-type

Probe: $\alpha$-particles from a radioactive source

Target: Gold Foil

Detectors: ZnS screen + human eyes

Detection Technique: Observe & count in a dark room tiny flashes when the particles hit the screen

Reasoned that large deflections observed are due to a tiny, massive, +vely charged core in the atom. $\Rightarrow$ "nucleus"

Nobel Prize: 1908.

# Electron, The First Elementary Particle

J. J. Thomson and his colleagues at Cavendish steadily improved the CRT. Thomson studied cathode rays in electric and magnetic fields

1897 - measures $e/m = 1.8 \times 10^{-11}$ Coulombs/kg

independent of gas, cathode material, voltage

1899 - measures electric charge $e$

$\Rightarrow m_e \simeq \frac{1}{2000} \times m_H$

J. J. at Cavendish

Nobel Prize: 1906

# The "Becquerel Rays"

Henri Becquerel (Paris)

- Thinks X-rays may be similar to phosphorescence he was studying
- conducts random experimentation
- By sheer luck (some frustration + curiosity) develops photographic plates he stored with chunks of Uranium salts and finds dark blotches

⇒ some invisible radiation spontaneously emitted by the U compound

Becquerel Rays did not become an instantaneous sensation like X-rays

But, ..

# 1930 - 32 Major Developments in Accelerators

- Cockroft & Walton Electrostatic Accelerator

  Protons accelerated to 770 keV
  at The Cavendish Lab
  (NP: 1951)

- Rober van de Graaff invents his electrostatic machine which reach 1.5 MeV

- Ernest O. Lawrence invents the Cyclotron

  - 4" machine with energy ~1 MeV

  37" machine at LBL in 1937

  (NP: 1939)

# Anti particles make their Debut

- In 1931 Paul Dirac writes down his famous equation

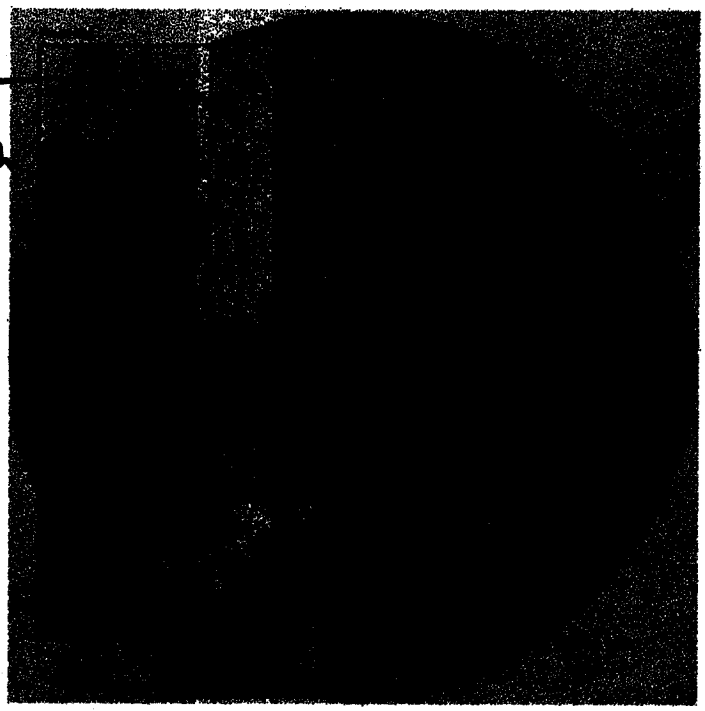
$$\gamma_\mu \left( \frac{\partial}{\partial x_\mu} + m \right) \psi = 0$$

and predicts the positron

– the "anti-particle" concept that humans had to comprehend for the first Time.

- 1933 Carl Anderson discovers the positron

Anderson's prize →
A cloud chamber photograph of a positron from Cosmic ray exposure



Paul Dirac → (NP: 1933)

↑ Carl Anderson Nobel Prize: 1936

Particle discoveries continued with exposure of nuclear emulsions and cloud chambers to cosmic rays.

Kaons ("V" events)

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

observed in 1947 in cloud chamber by Rochester & Butler

# Nuclear Emulsions

Photographic plates pave the way to Nuclear emulsions

Exposed to cosmic rays, accelerator beam, scanned and measured at later time.

Pion discovered in 1947 via

$$\pi \rightarrow \mu + \nu \rightarrow e + \nu + \nu$$

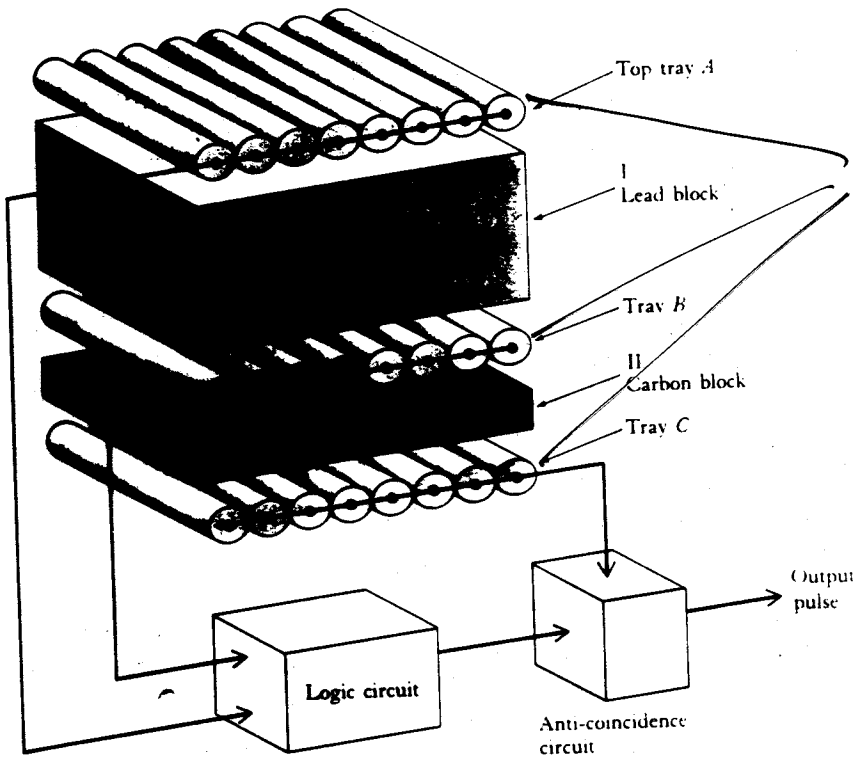
Peak activity between 1940-60

Powell receives Nobel Prize in

Resurgence in activities with emulsions in 1980's to study short-lived particles

Recently, The DONUT experiment at Fermilab used emulsions in the discovery of the $\nu_\tau$ (2000)

# Triggers for HEP




Geiger Counters

Bruno Rossi pioneers in coincidence, anti-coincidence circuits, & triggering.

Measures lifetime of the muon in 1943

# The Cloud Chamber Detects the Muon

Blackett and Occhialini added Geiger counters to control sensitizing of the cloud chamber. Photographs with great clarity emerged.

← Hybrid Detectors

By 1936, Anderson and Neddermeyer had cloud chamber candiates for a particle with mass intermediate between electron and proton. These were muons, but mistaken for Yukawa's pions until 1947.

(I. I. Rabi's famous comment on muon:
"Who ordered that?")

# The Second-half of The 20th Century

1950's Accelerators began to dominate the field of Particle Physics

Cyclotron → Synchrocyclotron
→ Synchrotron

400 MeV Nevis Accelerator (Design: 1945)

3 GeV Cosmotron at Brookhaven (1953)

6 GeV Bevatron at LBL (1955)

"Strong Focusing" – a seminal discovery in 1952.

25 GeV Proton Synchrotron PS at CERN (1959)

30 GeV AGS at BNL (1960)

The GeV range accelerators bring secondary beams ($\pi$, k beams)
"Particle Explosion"

Detectors had to catch up!

They had to

- handle high intensity beams
- be ready for a new beam cycle in matter of seconds, µs, . .

1956 Bubble chamber Donald Glaser

- principle similar to cloud chamber, bubble formation replaces droplet formation

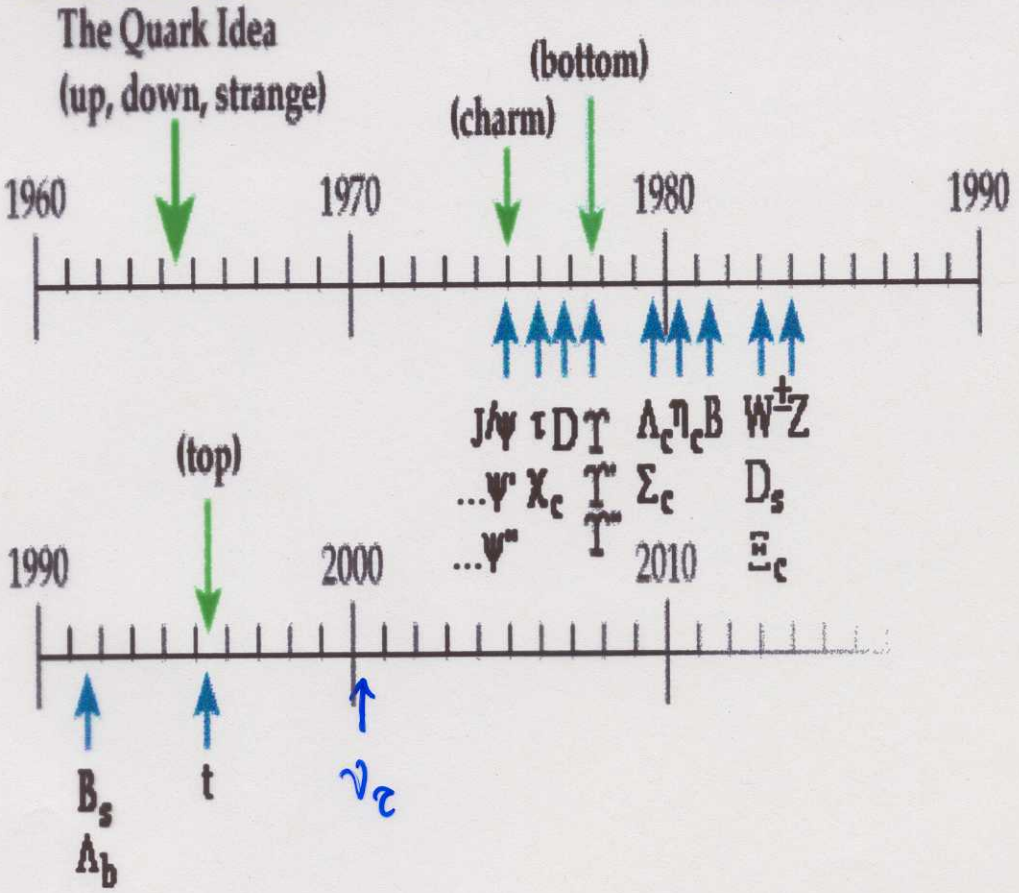
The Bubble chamber dominated the scene from 1960's - mid-1980's

A variety of successful experiments including the two ☺ participated in 1980's

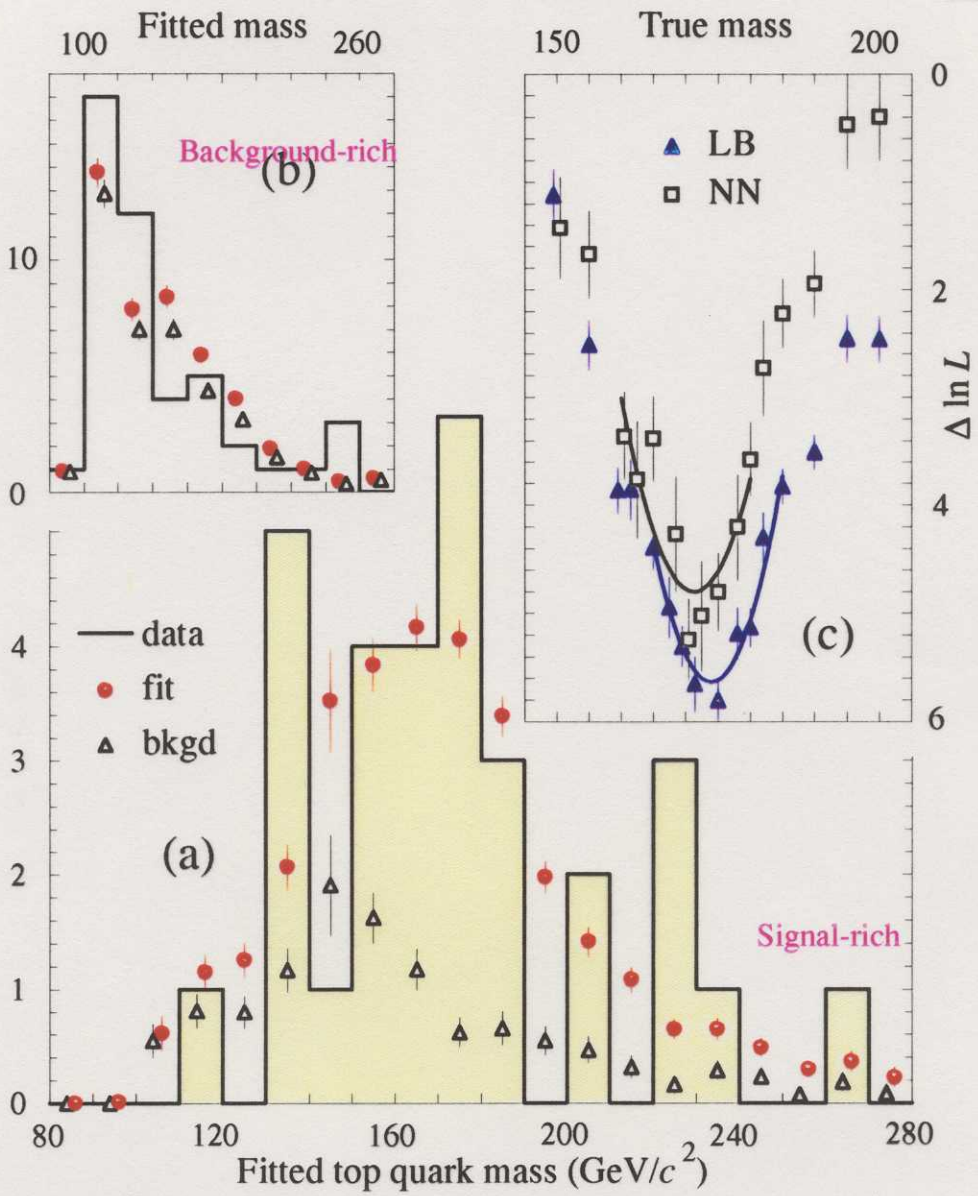
E-597 Hadron-nuclear Interactions

E-743 Hadro-production of Charm

# Particles discovered 1964 - present:



# DØ Lepton+jets Top Mass




LB Fit: 174.0 ± 5.6(stat.) GeV/$c^2$

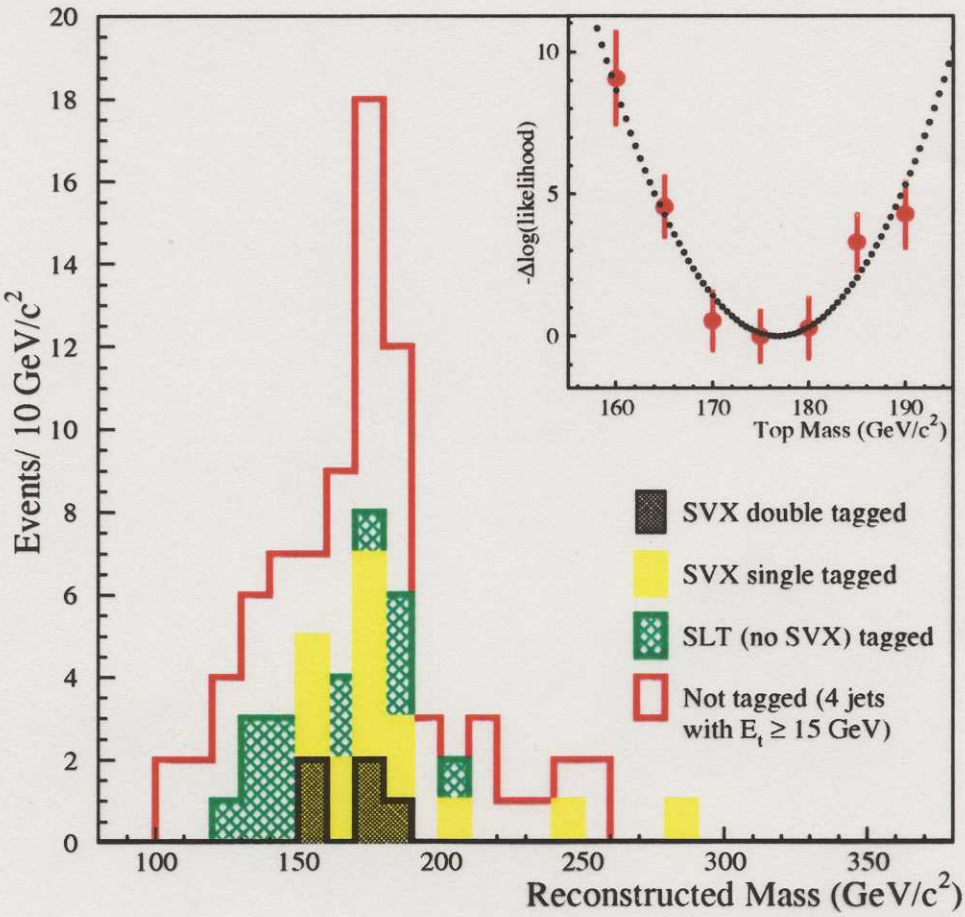
NN Fit: 171.3 ± 6.0(stat.) GeV/$c^2$

Correlation between LB and NN fits = (88 ±4)%

$m_t$ = 173.3 ± 5.6(stat.) ± 6.2 (syst.) GeV/$c^2$

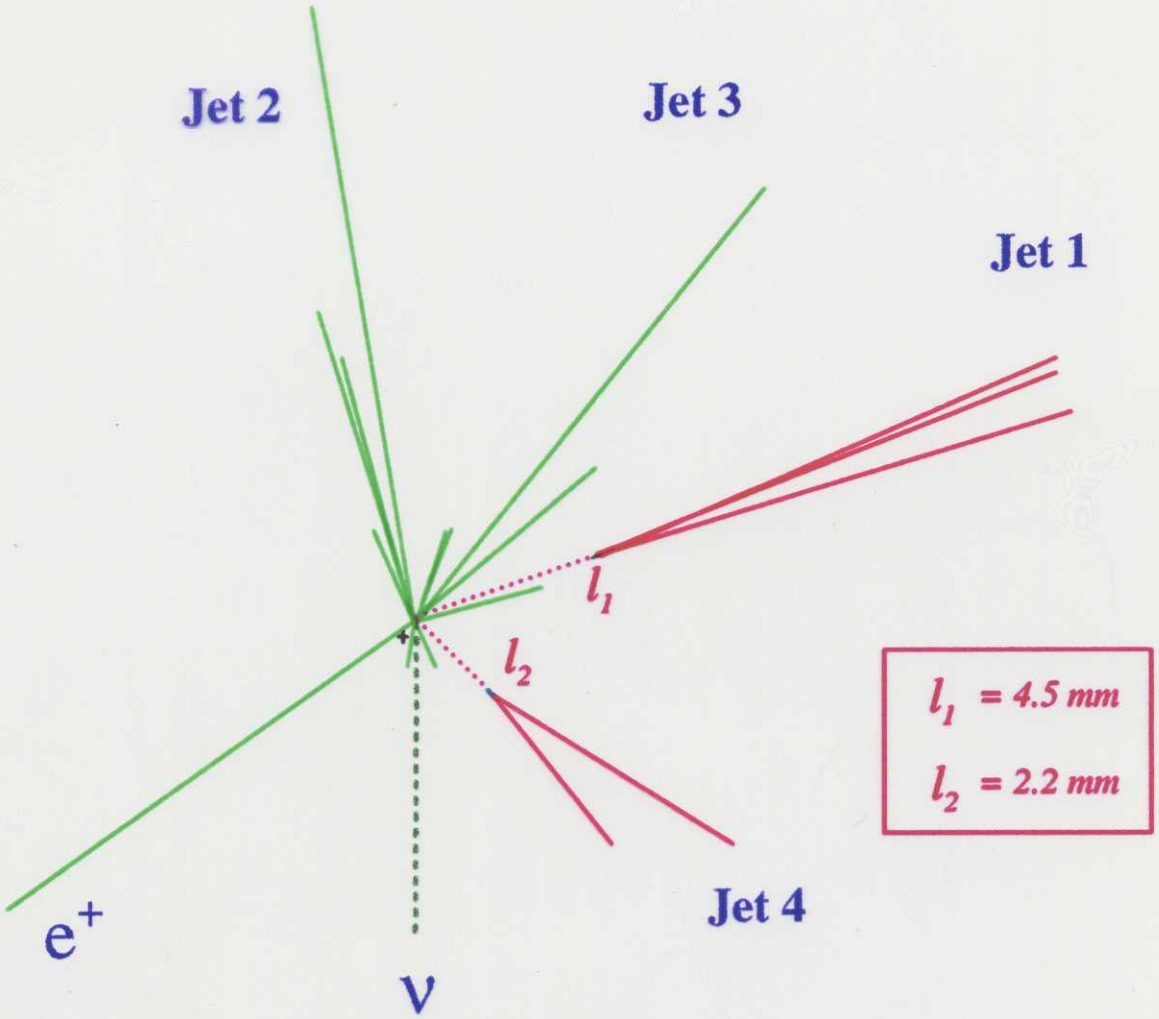
# CDF Lepton + Jets Top Mass

- Final likelihood is product of sub-sample likelihoods.

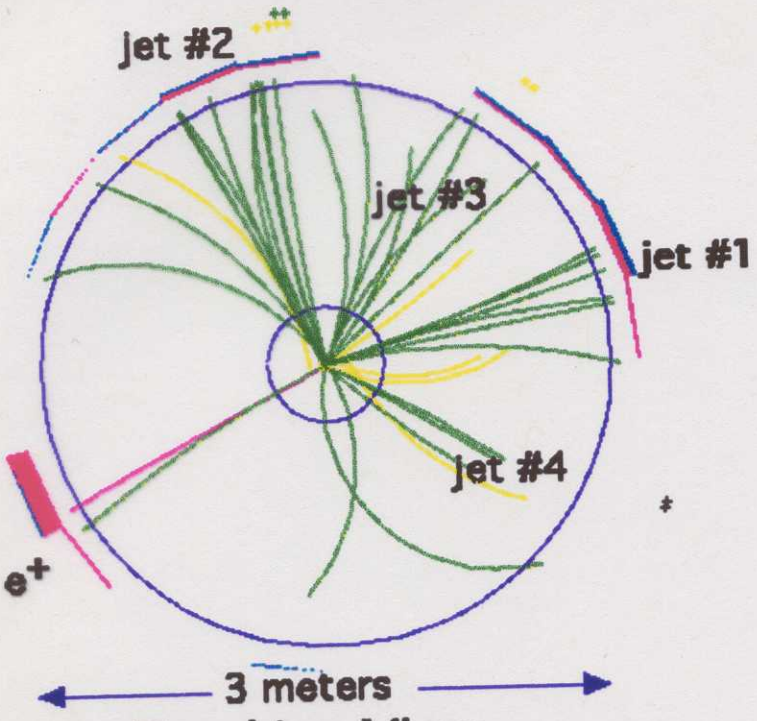



$m_t = 176.8 \pm 4.4$ (stat.) $\pm 4.8$ (syst.) GeV/$c^2$

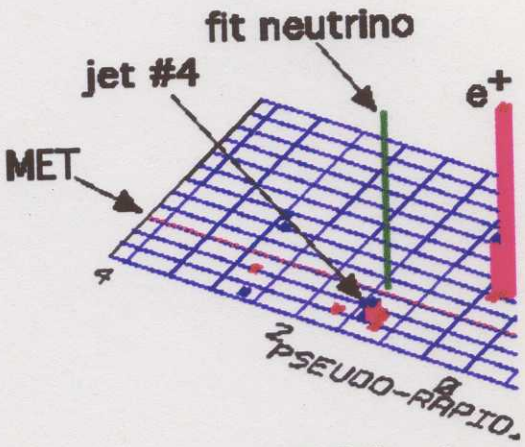
# CDF



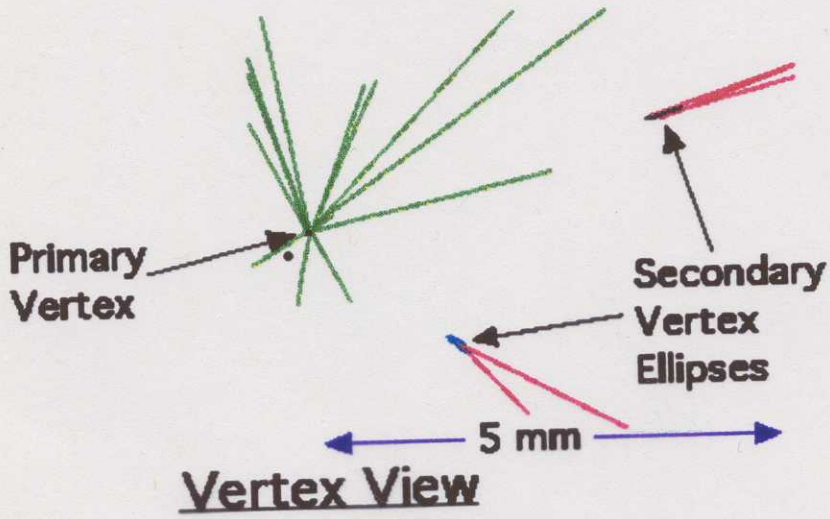
# e + 4 jet event




Tracking View




LEGO view

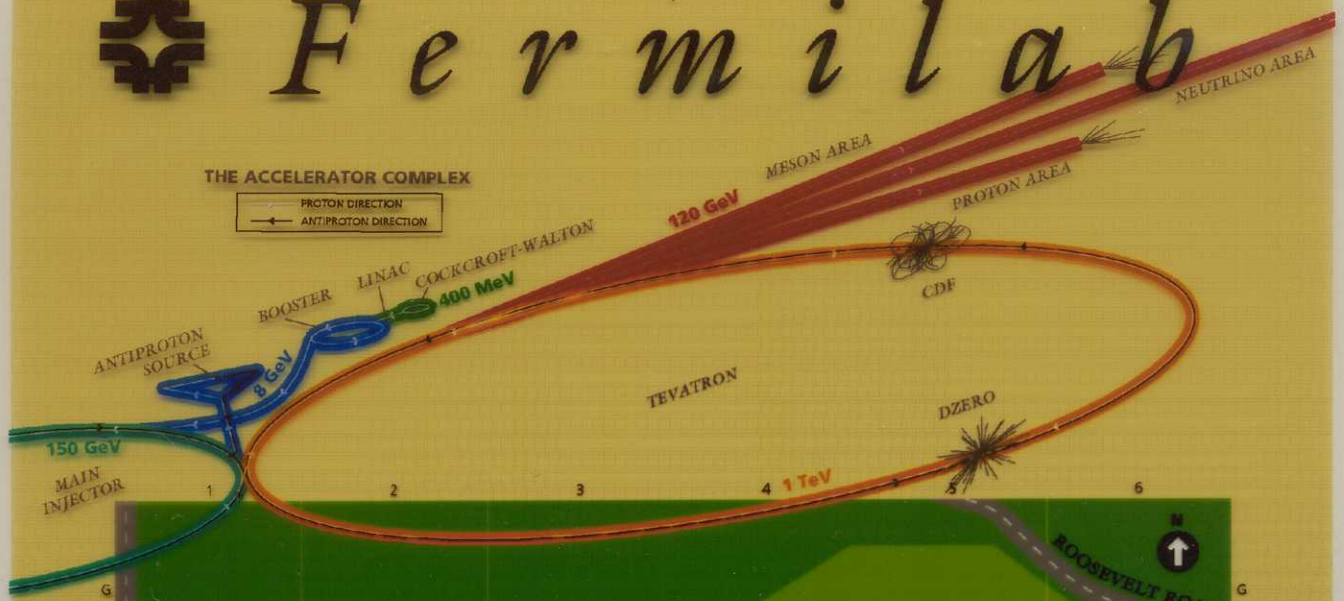



Vertex View

Courtesy of CDF collaboration

"GOLDEN" Top Event - This event has a 109 GeV $e^+$, and 4 Jets of (1) 90, (2) 77, (3) 64, and (4) 38 GeV. Jets (1) & (4)are tagged as b-jets by the CDF

# Fermilab





FERMILAB A Department of Energy National Laboratory

1 MILE
1 KILOMETER

Fermilab 95-734A

CERN: 1973-74 Neutral Current

1983 $W^{\pm}$, Z

Fermilab: 1977 b-quark

1995 t-quark

2000 $\nu_\tau$

# MAJOR DISCOVERIES AT MODERN ACCELERATORS

AGS: 1961-62 $\nu_e$, $\nu_\mu$

1964 CP violation in kaons

1974 Charm "J" for Ting

"The November Revolution"

SLAC: 1967-69 Quarks Sub-structure of nucleons

1974 Charm "ψ" for Richter

1976 τ- lepton

2001 CP violation in b system

DESY 1979 Evidence for gluon

The next major break-through in Particle Physics came with:

- Mass production of $\bar{p}$ in the Lab (proposed first by Budker in 1966)
- Stochastic cooling (1968)
- Collider Concept (first by Budker 1966, Rubbia et al 1977)

$S p\bar{p}S$ at CERN

- delivers first collisions in 1981
- delivers the discovery of W, Z in 1983
- Nobel Prizes to Rubbia, van der Meer

Linear Electron Accelerator at SLAC

20 GeV 1967

Deep inelastic Scattering of electrons off Nucleons.

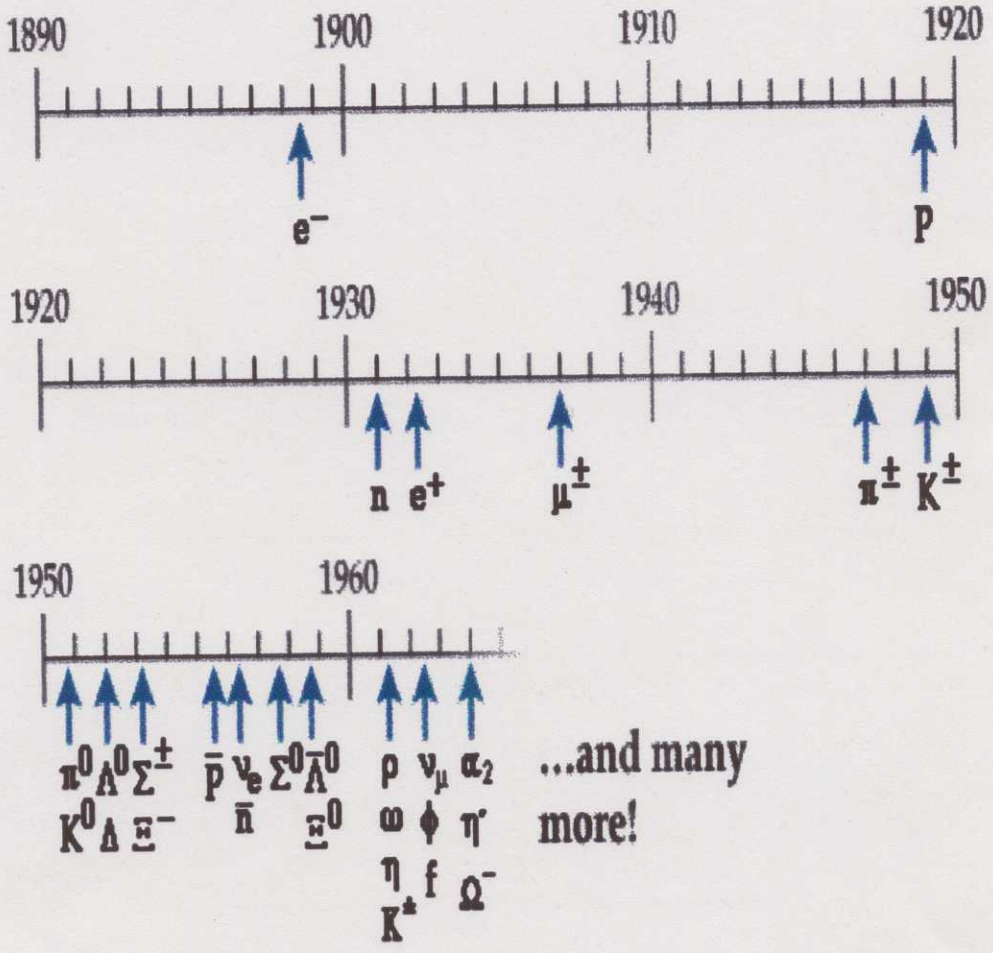
← Uncovers constituents of nucleons

Gellmann's quarks, Zweig's "aces"

Feynman calls them "partons"

← Rutherford Scattering all over again

**Particles discovered 1898 - 1964:**



# Detectors in the 2nd Half

## Scintillation Counters:

Modern version of Röntgen & Rutherford's scintillation screens

Very high time resolution

Used extensively since 50's & 60's

## Multi-wire Proportional Chambers:

Invented by Georges Charpak 1969 (Nobel Prize in 1992)

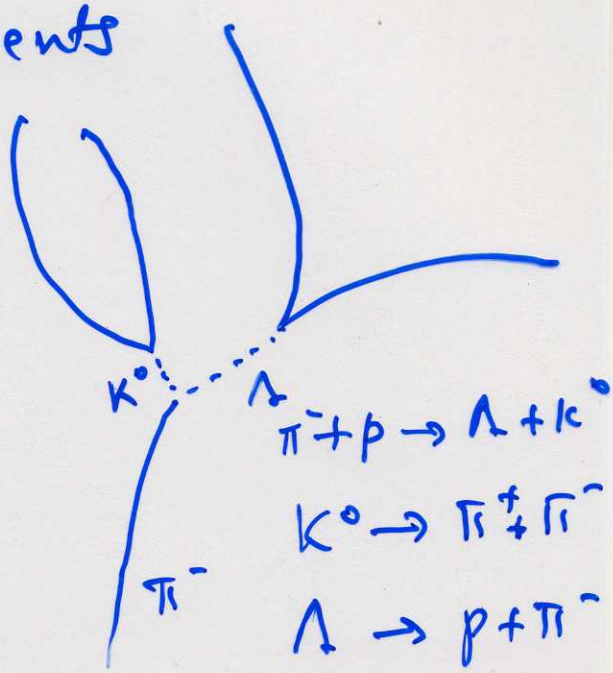
Dramatic break-through for spatial and temporal definition of particles

And then,... all the rest we will talk about

# Production of Hyperons in accelerator experiments

Cloud chamber @ the cosmotron

Bubble chamber @ CERN




Discovery of Anti proton at the Berkeley Bevatron

Chamberlain, Segre, Wiegand, Ypsilantis 1955

Uses Scintillators, Cerenkov Counters

W. D. Walker & P. C. Bhat in
Advanced Series on Directions in HEP, Vol. 2



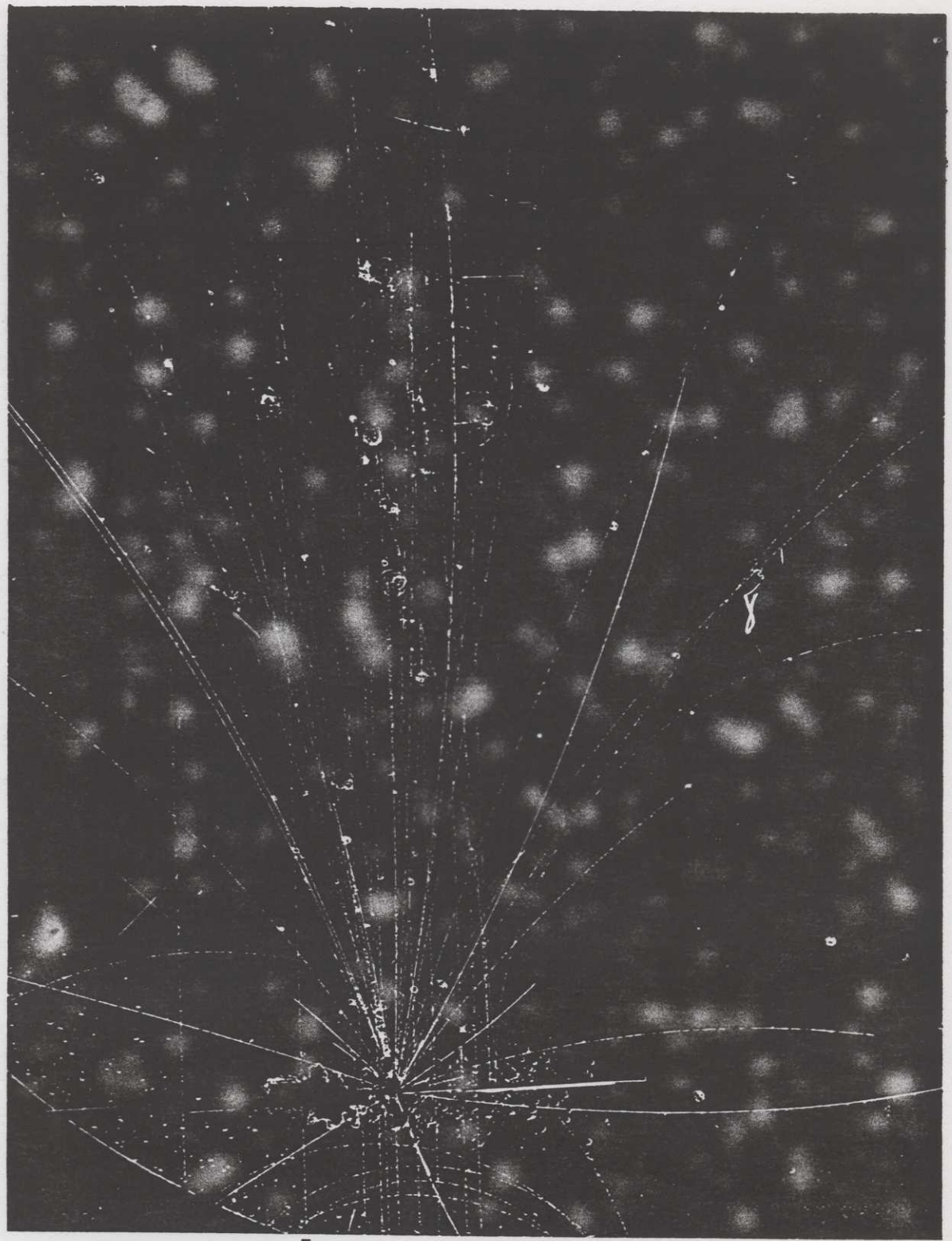


Figure 1: A $\pi^-$ gold collision occurring in a .3 mm thick gold foil. There are 14 or 15 identifiable protons emerging from the collision as well as 11 positive and 12 negative minimum ionizing particles.

1986

30" Hydrogen BC