# Physics 661

## Particle Physics Phenomenology

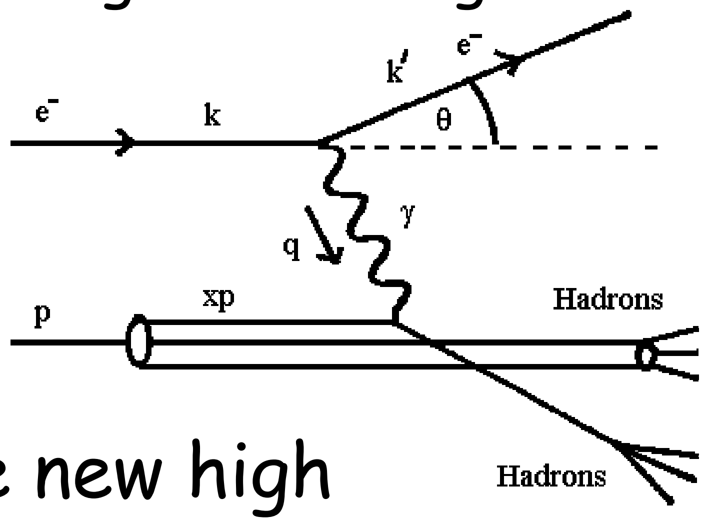
October 14, 2003

# Quarks and Leptons

- Elem. Particles and High Energy Physics
- Fixed Targets and Colliding Beams
- The Standard Model
  - fundamental fermions, interactions, time scales
- Limitations of the Standard Model
- Fermions and Bosons
- Particles and Antiparticles
- Free Particles and their wave equations
- Helicity States
- Lepton Flavors
- Quark Flavors

# Elementary particles and High Energy Physics

- In order to explore the substructure of matter we need to go to <u>high energy</u>
  - resolution is limited by deBroglie wavelength
  - $\lambda = h/p$




- Also, in order to produce new high mass particles we need <u>higher energy</u>

# Fixed Target and Colliding Beam Accelerators

- Early experiments were done with a beam of particles and a fixed target
  - The energy in the center-of-mass is

    $s \equiv E_{cm}^2 = (E_{beam} + m_{target})^2 - p_{beam}^2$

    $= 2\, E_{beam}\, m_{target} + m_{target}^2 + m_{beam}^2$
  - $E_{cm}$ only increases as the square root of $E_{beam}$

    (note $\sqrt{s} \equiv E_{cm}$)
- By colliding beams of particles, $E_{cm}$ increases linearly with $E_{beam}$

  $s \equiv E_{cm}^2 = (E_{beam} + E_{beam})^2 - (p_{beam} - p_{beam})^2$

  $= 4\, E_{beam}^2$

# Colliding Beam Experiments

- Most experiments today are done with colliding beams
  - CDF (Fermilab)
  - D0 (Fermilab)
    - $p\bar{p}$ @ 1 TeV/beam
    - highest energy in world - currently

  - BaBar (SLAC) 3 GeV $e^+$ $\otimes$ 9 GeV $e^-$
    - B Factory

# The Standard Model

A very successful model of elementary particles and their interactions was been developed (~1970s). It has stood up to all experimental tests, but we know it is incomplete

- The fundamental fermions
- The interactions
- The limitations

# The Fundamental Fermions

- All matter is built from small number of fermions (spin 1/2) particles
- Leptons (integer charge) - six 'flavors'
  - charged leptons (electron, muon, tau)
    - $\tau$(muon) = 2.2 microsec $\tau$(tau) = 0.3 picosec.
  - neutral leptons (electron-neutrino, muon-neutrino, tau-neutrino)
- Quarks (fractional charge) - six 'flavors'
  - up-type quarks (up, charm, top)
  - down-type (down, strange, bottom)
    - only up and down are stable

# The Fundamental Fermions

**FERMIONS** matter constituents
spin = 1/2, 3/2, 5/2, ...

**Leptons** spin = 1/2

| Flavor | Mass GeV/$c^2$ | Electric charge |
|---|---|---|
| $\nu_e$ electron neutrino | $<1\times10^{-8}$ | 0 |
| $e$ electron | 0.000511 | −1 |
| $\nu_\mu$ muon neutrino | <0.0002 | 0 |
| $\mu$ muon | 0.106 | −1 |
| $\nu_\tau$ tau neutrino | <0.02 | 0 |
| $\tau$ tau | 1.7771 | −1 |

**Quarks** spin = 1/2

| Flavor | Approx. Mass GeV/$c^2$ | Electric charge |
|---|---|---|
| u up | 0.003 | 2/3 |
| d down | 0.006 | −1/3 |
| c charm | 1.3 | 2/3 |
| s strange | 0.1 | −1/3 |
| t top | 175 | 2/3 |
| b bottom | 4.3 | −1/3 |

# Fundamental Fermions in Nature

- Leptons exist as free particles
- Quarks have never been observed as free particles, only bound within composites, such as the proton (uud), the neutron (udd), the pion (u, anti-d), etc.
- This property of quarks is called 'confinement' and it is an important property of the strong interaction
- The stable particles are the lightest: the electron, u and d quarks, neutrinos.

# The Interactions

- Strong
  - binds quarks, mediated by gluon (massless, spin 1)
- Electromagnetic
  - binds electrons in the atom (mediated by photon)
- Weak
  - responsible for $\beta$ decay; mediated by $W^{\pm}$, $Z^0$ (massive, spin 1)
- Gravity
  - force between all matter, mediated by graviton (massless, spin 2)

# The Interactions

| | Gravity | Electromag. | Weak | Strong |
|---|---|---|---|---|
| field boson | graviton | photon | $W^{\pm}$,Z | gluon |
| spin-parity | $2^+$ | $1^-$ | $1^-$, $1^+$ | $1^-$ |
| mass, GeV | 0 | 0 | $M_W$=80.2<br>$M_Z$=91.2 | 0 |
| range, m | ∞ | ∞ | $10^{-18}$ | $\leq 10^{-15}$ |
| source | mass | electric charge | 'weak' charge | 'color' charge |
| coupling constant | $5 \times 10^{-40}$ | 1/137 | $1.2 \times 10^{-5}$ | $\leq 1$ |
| typical cross-section, $m^2$ | | $10^{-33}$ | $10^{-39}$ | $10^{-30}$ |
| typical lifetime, s | | $10^{-20}$ | $10^{-10}$ | $10^{-23}$ |

# Measuring the time scales

- Timescales of $10^{-10}$ seconds are straightforward, since particles typically travel at the speed of light, and distances of many mm are involved
- Shorter times can be more difficult
- Consider the time scale of the strong interaction: $10^{-23}$ sec
  - for these particles, we must measure the 'width'

    $\Gamma = h/2\pi\tau$ (uncertainty principle)

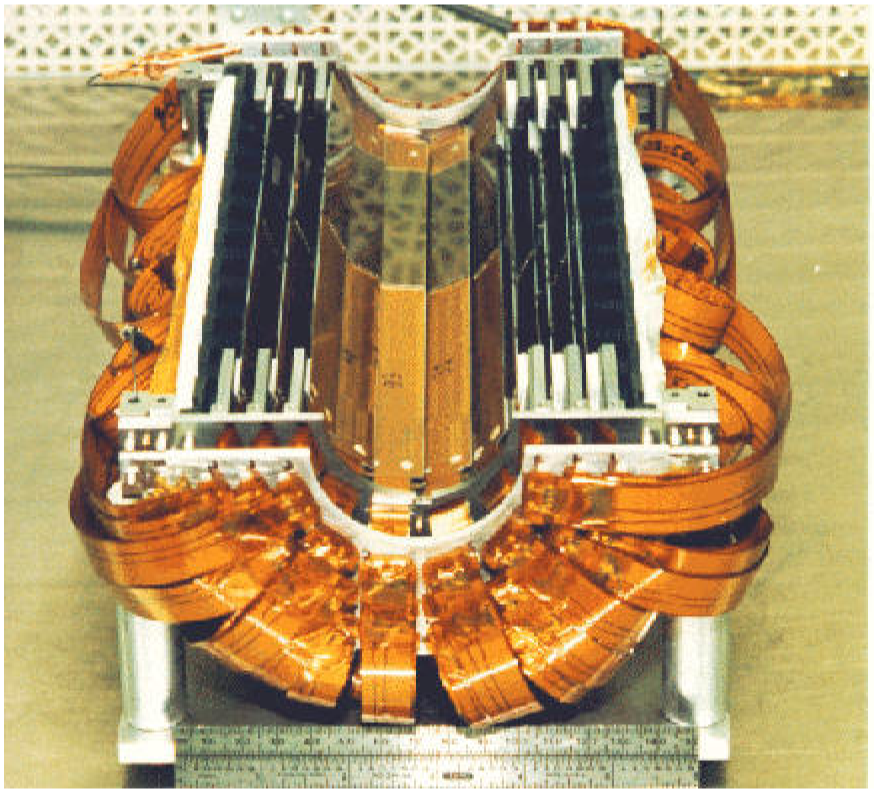
# Measuring the time scales

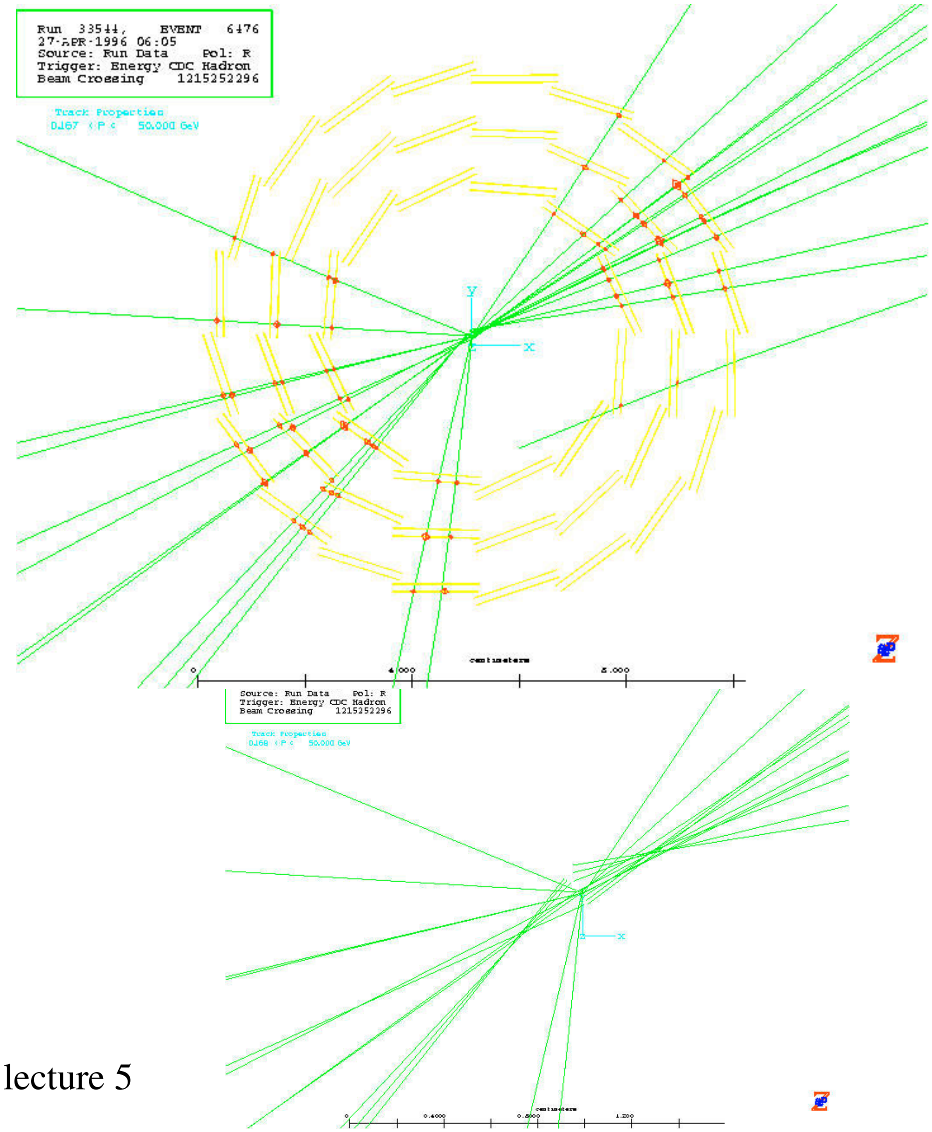
- If a particle travels millimeters, we can measure its trajectory with precision detectors (vertex detectors)

$$d = c\,\tau$$
$$= 3 \times 10^{10}\ \text{cm/sec}\quad \tau$$
$$= 3\ \text{mm} / 10^{-11}\ \text{sec}\quad \tau$$
$$= 3\ \text{mm}\quad \tau / 10^{-11}\ \text{sec}$$

(we can actually measure sub-millimeter flight distances)

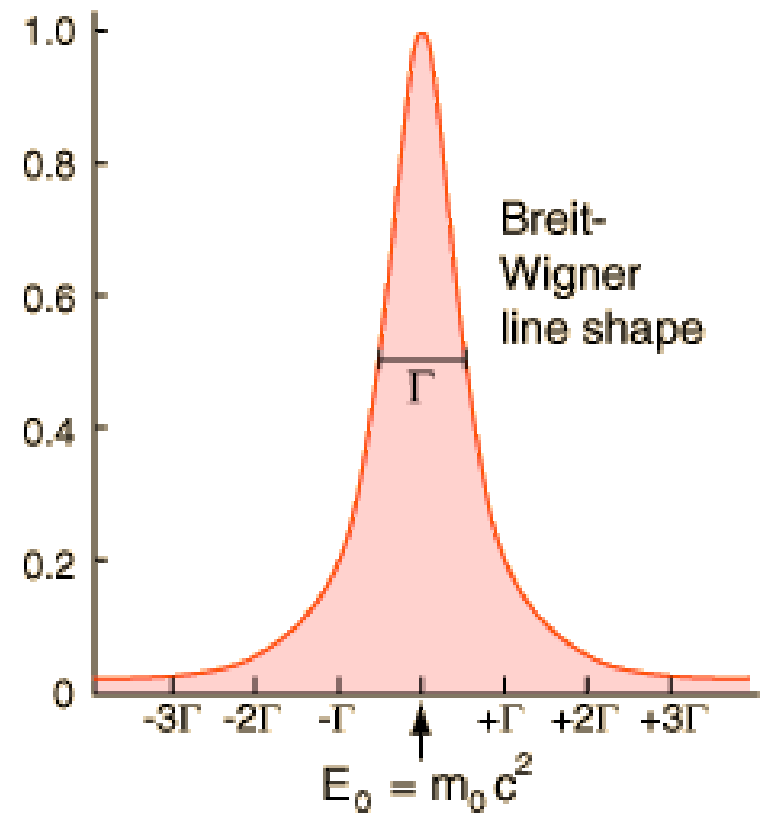
# Vertex Detector





# Measuring the time scales

- The uncertainty principle tells us that if we try to measure the mass of an unstable particle, there will be an uncertainty in that measurement
  - $\Delta E \Delta t > h/4\pi$
  - $\Gamma(\mathrm{MeV}/c^2) = 7 \times 10^{-22}\mathrm{sec} / \tau$




http://230nsc1.phy-astr.gsu.edu/hbase/quantum/parlif.html

# The Limitations of the Standard Model

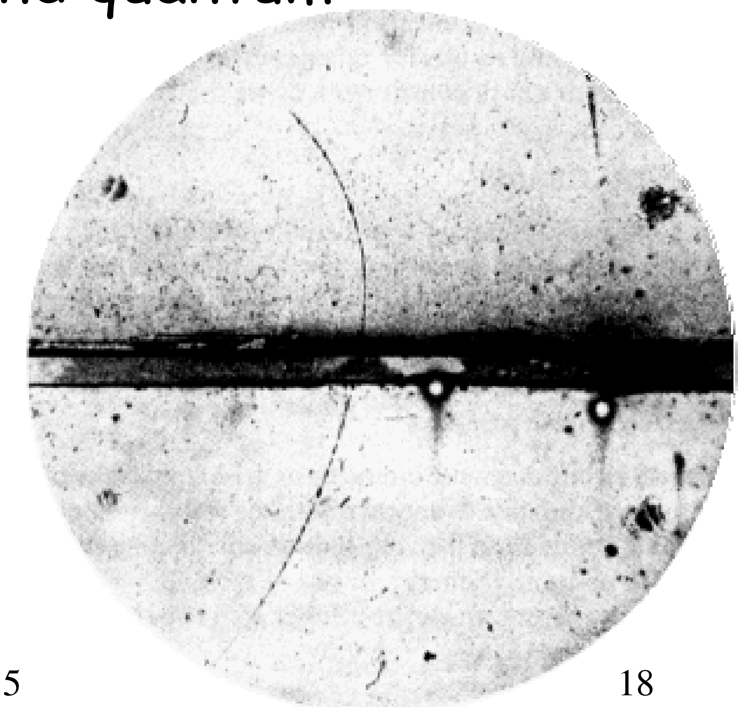
- Gravity is not explicitly included
- Neutrinos are assumed to be massless
- 17 arbitrary constants
  - masses (9) quarks and charged leptons
  - mixing angles (4) CKM matrix for the quarks
  - coupling constants (4) $G_F$, $\alpha$, $\alpha_s$, $\sin^2\theta_w$
- Six 'copies' of quarks and leptons assumed without understanding of reason for six
- Dark matter is not understood

# Bosons and Fermions

- The fundamental particles are fermions (spin 1/2), but bosons can be constructed from even numbers of the fund. fermions
- For example, the pions are bosons and obey bose-statistics
- The application of Fermi-Dirac and Bose-Einstein statistics is important in the study of the fundamental particles, and we will make use of it:
  - an example is the understanding of the $\Delta^{++}$ = (uuu) particle, which led to the realization of a new quantum number, color

# The particles and antiparticles

- Every particle has a corresponding antiparticle, with the same mass and lifetime, and opposite charge and magnetic moment
- Dirac predicted this from fundamental considerations of relativity and quantum mechanics
- The first antiparticle, the positron, was discovered in 1932 in a cloud chamber experiment with cosmic rays



# Particle and antiparticles

- Both bosons and fermions have antiparticles, however for fermions there is a conservation law: the difference in the number of fermions and antifermions is a constant
- This law is the origin of the conservation of baryons number and lepton family number:
  - $n \to p\, e^- \overline{\nu_e}$
  - $\pi^- \to \mu^- \overline{\nu_\mu}$
  - $\mu^- \to e^- \overline{\nu_e}\, \nu_\mu$

# Particle and antiparticles

- This conservation law does not exist for bosons, so that the following reactions are all possible
  - $p\ p \rightarrow p\ p\ \pi$
  - $p\ p \rightarrow p\ p\ \pi\ \pi$
  - $p\ p \rightarrow p\ p\ \pi\ \pi\ \pi$

- A boson may be its own antiparticle
  - eq. $\pi^0$