PHYS 3446 – Lecture #19

Wednesday, Apr. 13, 2005
Dr. Jae Yu

- Parity
  - Determination of Parity
  - Parity Violation
- Time Reversal and Charge Conjugation
- The Standard Model
  - Quarks and Leptons
  - Gauge Bosons
  - Symmetry Breaking and the Higgs particle

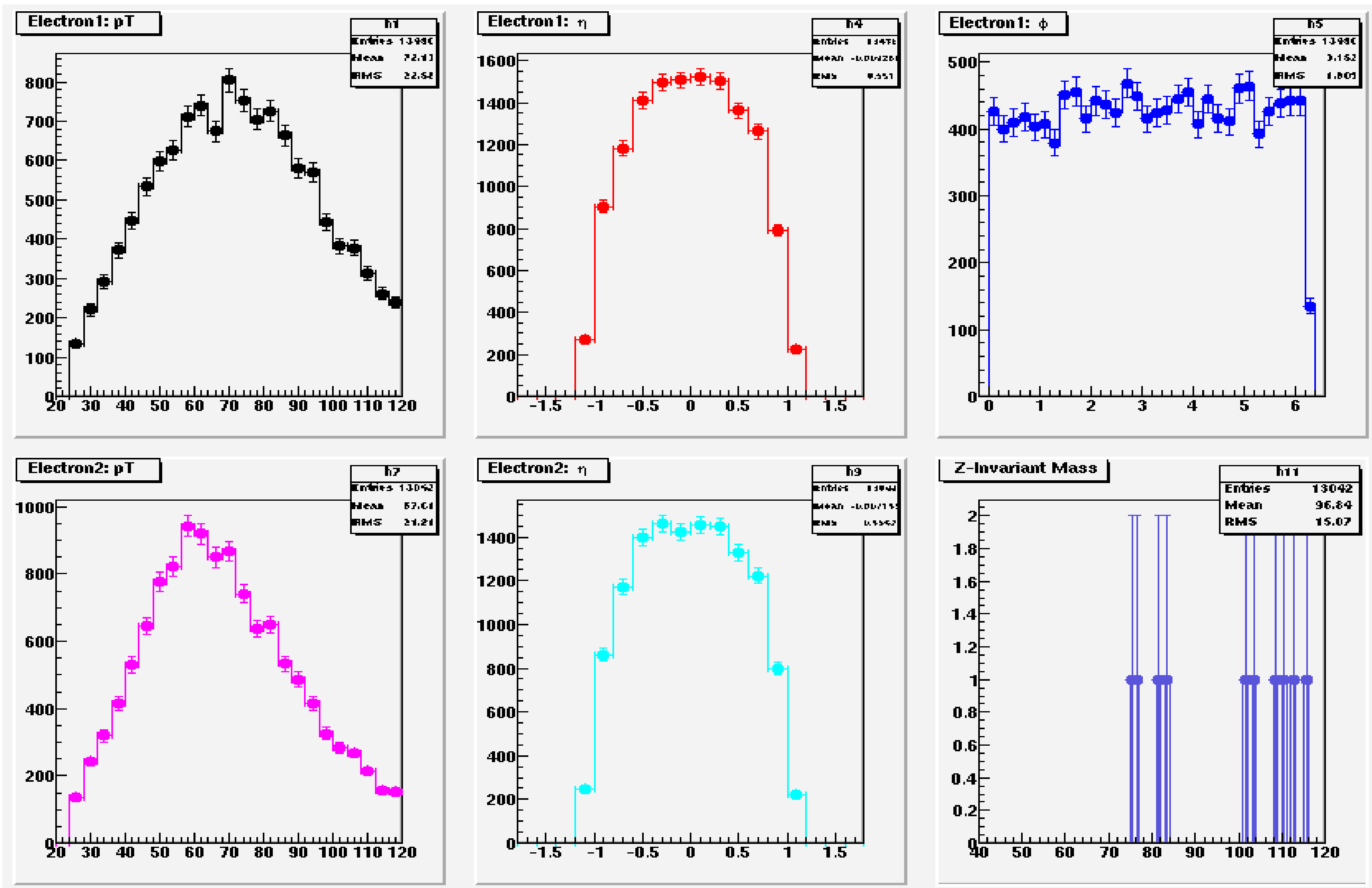
Announcements

- The final quiz next Wednesday, Apr. 20
  - At 1:05pm, in the class (SH200)
  - Covers: Ch 10 – what we cover on Monday, Apr. 18
- Macros for your project analysis ready and released yesterday morning
- Due for your project write up is Friday, April 22
  - How are your analyses coming along?
- Keep in mind the final, final homework due is Apr. 20.
- I still need to see a few more of you for individual semester grade discussion.

Project root and macro file locations

- All hanging from the directory /home/venkat/PHYS3446/
- W events
  - ```
    |-- W-E-Nu
    |   |-- MakeTMBTreeClasses_so.C
    |   |-- RunMC.C
    |   |-- TMBTree_bu.C
    |   `-- TMBTree_bu.h
    ```
  - ```
    |-- W-Mu-Nu
    |   |-- MakeTMBTreeClasses_so.C
    |   |-- RunMC.C
    |   |-- TMBTree_bu.C
    |   `-- TMBTree_bu.h
    ```
- Z events
  - ```
    |-- Z-E-E
    |   |-- MakeTMBTreeClasses_so.C
    |   |-- RunMC.C
    |   |-- TMBTree_bu.C
    |   `-- TMBTree_bu.h
    ```
  - ```
    `-- Z-Mu-Mu
        |-- MakeTMBTreeClasses_so.C
        |-- RunMC.C
        |-- TMBTree_bu.C
        `-- TMBTree_bu.h
    ```

Output of Z→e+e+X macro



Gauge Fields and Mediators

- To keep local gauge invariance, new particles had to be introduced in gauge theories
  - U(1) gauge introduced a new field (particle) that mediates the electromagnetic force: Photon
  - SU(2) gauge introduces three new fields that mediates weak force
    - Charged current mediator: W^+ and W^-
    - Neutral current: Z^0
  - SU(3) gauge introduces 8 mediators for the strong force
- Unification of electromagnetic and weak force SU(2)xU(1) introduces a total of four mediators
  - Neutral current: Photon, Z^0
  - Charged current: W^+ and W^-

Parity

- The space inversion transformation (mirror image) ➔ Switch right- handed coordinate system to left-handed

$$\begin{pmatrix} ct \\ x \\ y \\ z \end{pmatrix} \xrightarrow{Parity} \begin{pmatrix} ct \\ -x \\ -y \\ -z \end{pmatrix}$$

- How is this different than spatial rotation?
  - Rotation is continuous in a given coordinate system
    - Quantum numbers related rotational transformation are continuous
  - Space inversion cannot be obtained through any set of rotational transformation
    - Quantum numbers related to space inversion is discrete

Determination of Parity Quantum Numbers

- How do we find out the intrinsic parity of particles?
  - Use observation of decays and production processes
  - Absolute determination of parity is not possible, just like electrical charge or other quantum numbers.
  - Thus the accepted convention is to assign <u>+1 intrinsic parity to proton, neutron and the Λ hyperon</u>.
    - The parities of other particles are determined relative to these assignments through the analysis of parity conserving interactions involving these particles.

Parity Determination

- When the parity is conserved, it can restrict decay processes that can take place.
- Consider a parity conserving decay: A→B+C
  - Conservation of angular momentum requires both sides to have the same total angular momentum J.
  - If B and C are spinless, their relative orbital angular momentum (ℓ) must be the same as J(=l+s).
  - Thus conservation of parity implies that

$$\eta_A = \eta_B \eta_C \left(-1\right)^l = \eta_B \eta_C \left(-1\right)^J$$

  - If the decay products have spin zero, for the reaction to take place we must have $\eta_A = \eta_B \eta_C$ between the intrinsic parities

Parity Determination

- Therefore, the allowed decays must have

$$0^{+} \rightarrow 0^{+} + 0^{+}$$

$$0^{+} \rightarrow 0^{-} + 0^{-}$$

$$0^{-} \rightarrow 0^{+} + 0^{-}$$

  – Where the spin intrinsic parity if particles are expressed as J^P

- The following decays are prohibited under parity conservation

$$0^{+} \not\rightarrow 0^{+} + 0^{-}$$

$$0^{-} \not\rightarrow 0^{-} + 0^{-}$$

$$0^{-} \not\rightarrow 0^{+} + 0^{+}$$

Example 1, π^- parity

- Consider the absorption of low energy π^- in deuterium nuclei

$$\pi^- + d \rightarrow n + n$$

- The conservation of parity would require

$$\eta_{\pi^-}\eta_d\left(-1\right)^{l_i} = \eta_n\eta_n\left(-1\right)^{l_f}$$

- Since the intrinsic parity of deuteron is +1, and that of the two neutrons is +1,

$$\eta_{\pi^-} = \left(-1\right)^{l_f - l_i} = \left(-1\right)^{l_f + l_i}$$

- This capture process is known to proceed from an li=0 state, thus we obtain $\eta_{\pi^-} = \left(-1\right)^{l_f}$

Example 1, π^- parity, cont'd

- Since spin of the deuteron J_d=1, only a few possible states are allowed for the final state neutrons

$$1)\quad |nn\rangle = |J=1,\ s=1,\ l_f=0 \text{ or } 2\rangle$$

$$2)\quad |nn\rangle = |J=1,\ s=1,\ l_f=1\rangle$$

$$3)\quad |nn\rangle = |J=1,\ s=0,\ l_f=1\rangle$$

- Since the two neutrons are identical fermions, their overall wave functions must be anti-symmetric due to Pauli's exclusion principle ➔ leaves only (3) as the possible solution
- Making pion a pseudo-scalar w/ intrinsic parity $\eta_{\pi^-} = -1$

Parity Violation

- Till the observation of "τ–θ" puzzle in cosmic ray decays late 1950's, parity was thought to be conserved in (symmetry of) all fundamental interactions
- The τ and θ particles seem to have identical mass, lifetimes, and spin (J=0) but decay differently

$$\theta^{+} \to \pi^{+} + \pi^{0} \qquad \left(\eta_{\theta^{+}} = \eta_{\pi^{+}}\eta_{\pi^{0}} = \left(-1\right)^{2} = 1\right)$$

$$\tau^{+} \to \pi^{+} + \pi^{+} + \pi^{-} \qquad \left(\eta_{\tau^{+}} = \eta_{\pi^{+}}\eta_{\pi^{+}}\eta_{\pi^{-}} = \left(-1\right)^{3} = -1\right)$$

- These seem to be identical particles. Then, how could the same particle decay in two different manner, violating parity?

Parity Violation

- T.D. Lee and C.N. Yang studied all known weak decays and concluded that there were no evidences of parity conservation in weak decays
  - Postulated that weak interactions violate parity
  - See, http://ccreweb.org/documents/parity/parity.html for more interesting readings
- These turned out to be

$$K^+ \to \pi^+ + \pi^0 \quad \left(\mathrm{K}_{\pi 2}\right)$$

$$K^+ \to \pi^+ + \pi^+ + \pi^- \left(\mathrm{K}_{\pi 3}\right)$$

Time Reversal

- Invert time from t → - t .

$$t \xrightarrow{\mathrm{T}} -t$$

$$\vec{r} \xrightarrow{\mathrm{T}} \vec{r}$$

$$\vec{p} = m\dot{\vec{r}} \xrightarrow{\mathrm{T}} -m\dot{\vec{r}} = -\vec{p}$$

$$\vec{L} = \vec{r} \times \vec{p} \xrightarrow{\mathrm{T}} (\vec{r}) \times (-\vec{p}) = -\vec{r} \times \vec{p} = -\vec{L}$$

- How about Newton's equation of motion?

$$m\frac{d^2\vec{r}}{dt^2} = \vec{F} = \frac{C}{r^2}\hat{r} \xrightarrow{\mathrm{T}} m(-1)^2\frac{d^2\vec{r}}{dt^2} = m\frac{d^2\vec{r}}{dt^2} = \vec{F} = \frac{C}{r^2}\hat{r}$$

  – Invariant under time reversal

Charge Conjugate

- Conversion of charge from Q → - Q .

$$Q \xrightarrow{\mathrm{C}} -Q$$

$$\vec{E} = c\frac{q}{r^2}\hat{r} \xrightarrow{\mathrm{C}} c\frac{-q}{r^2}\hat{r} = -\vec{E}$$

$$\vec{B} = cI\int\frac{d\vec{s}\times\hat{r}}{r^2} \xrightarrow{\mathrm{C}} c\left(-I\right)\int\frac{d\vec{s}\times\hat{r}}{r^2} = -\vec{B}$$

- Under this operation, particles become antiparticles
- What happens to the Newton's equation of motion?

$$m\frac{d^2\vec{r}}{dt^2} = \vec{F} = \frac{C}{r^2}\hat{r} \xrightarrow{\mathrm{C}} m\frac{d^2\vec{r}}{dt^2} = \frac{q^2}{r^2}\left(-1\right)^2\hat{r} = \vec{F}$$

  – Invariant under charge conjugate

The Standard Model of Particle Physics

- Prior to 70's, low mass hadrons are thought to be the fundamental constituents of matter, despite some new particles that seemed to have new flavors
  - Even lightest hadrons, protons and neutrons, show some indication of substructure
    - Such as magnetic moment of the neutron
  - Questioning whether they really are fundamental particles
- In 1964 Gell-Mann and Zweig suggested independently that hadrons can be understood as composite of quark constituents
  - Recall that the quantum number assignments, such as strangeness, were only calculational tools rather than real particles

The Standard Model of Particle Physics

- In late 60's, Jerome Friedman, Henry Kendall and Rich Taylor designed an experiment with electron beam scattering off of hadrons and deuterium at SLAC (Stanford Linear Accelerator Center)
  - Data could be easily understood if protons and neutrons are composed of point-like objects with charges -1/3e and +2/3e.
  - A point-like electrons scattering off of point-like quark partons inside the nucleons and hadrons
    - Correspond to modern day Rutherford scattering
    - Higher energies of the incident electrons could break apart the target particles, revealing the internal structure

The Standard Model of Particle Physics

- Elastic scattering at high energies can be described well with the elastic form factors measured at low energies, why?
  - Since the interaction is elastic, they behave as if they are point-like particles
- Inelastic scattering, on the other hand, cannot be since the target is broken apart
  - Inelastic scatterings of electrons with large momentum transfer (q^2) provides opportunities to probe shorter distances, breaking apart nucleons
  - The fact that the form factor for inelastic scattering at large q^2 is independent of q^2 shows that there are point-like object in a nucleon
- Nucleons contain both quarks and glue particles (gluons) both described by individual characteristic momentum distributions (Parton Distribution Functions)

The Standard Model of Particle Physics

- By early 70's, it was clear that hadrons are not fundamental point-like objects
- But leptons did not show any evidence of internal structure
  - Event at very high energies they still do not show any structure
  - Can be regarded as elementary particles
- The phenomenological understanding along with observation from electron scattering (Deep Inelastic Scattering, DIS) and the quark model
- Resulted in the Standard Model that can describe three of the four known forces along with quarks, leptons and gauge bosons as the fundamental particles

Quarks and Leptons

- In SM, there are three families of leptons   Q

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \quad \begin{matrix} 0 \\ -1 \end{matrix}$$

  – ➔ Increasing order of lepton masses
  – Convention used in strong isospin symmetry, higher member of multiplet carries higher electrical charge

- And three families of quark constituents   Q

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix} \quad \begin{matrix} +2/3 \\ -1/3 \end{matrix}$$

- All these fundamental particles are fermions w/ spin $\frac{1}{2}\hbar$

Standard Model Elementary Particle Table

- Assumes the following fundamental structure:

- Total of 6 quarks, 6 leptons and 12 force mediators form the entire universe

Quark Content of Mesons

- Meson spins are measured to be integer.
  - They must consist of an even number of quarks
  - They can be described as bound states of quarks
- Quark compositions of some mesons
  - Pions

$$\pi^+ = u\bar{d}$$

$$\pi^- = \bar{u}d$$

$$\pi^0 = \frac{1}{\sqrt{2}}\left(u\bar{u} - d\bar{d}\right)$$

Strange mesons

$$K^+ = u\bar{s}$$

$$K^- = \bar{u}s$$

$$K^0 = d\bar{s}$$

$$\bar{K}^0 = \bar{d}s$$

Assignments

1. No homework today!!!