PHYS 5326 – Lecture #17

Monday, Mar. 24, 2003
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- Mid-term problem review
- Mass Terms in Lagrangians
- Spontaneous Symmetry Breaking
1. Conventional Neutrino Beam

- Use large number of protons on target to produce many secondary hadrons ($\pi$, $K$, $D$, etc) and focus as many of them as possible.
- Let $\pi$ and $K$ decay in-flight for $\nu_\mu$ beam in the decay pipe
  \[ \pi \rightarrow \mu + \nu_\mu \ (99.99\%), \ K \rightarrow \mu + \nu_\mu \ (63.5\%) \]
- Let the beam go through shield and dirt to filter out $\mu$ and remaining hadrons, except for $\nu$.
  - Dominated by $\nu_\mu$. 

Diagram:

- Good target
- Good beam focusing
- Sufficient dump
- Long decay region
- Lead/Steel/Dirt Shield
- Lab E Detector
2. How can we select sign of neutrinos?

- Neutrinos are electrically neutral
- Need to select the charge of the secondary hadrons from the proton interaction on target
- Sets of Dipoles are used to select desired charges of the secondary hadrons
3. How can there be wrong sign of neutrinos in a sign selected beam?

- Interaction of correct sign secondary hadrons with beamline elements, including dump and shields
  - Act as if a fixed target is hit by hadron beam
- Back-scatter of unused protons into the beamline
- CP violating neutrino oscillations
4. QCD Factorization Theorem

Factor the whole interaction into two independent parts!!

Allow QCD perturbation theory to work and physical observables calculable.

Partonic hard scatter

Non-perturbative, infra-red part $f$

$\sigma = f \star \sigma_p$

$W^+ (W^-)$

$p_\mu, \theta_\mu$

$E_{\text{Had}}$

$q, (\bar{q})$

$q = k - k'$

Factor the whole interaction into two independent parts!!

Allow QCD perturbation theory to work and physical observables calculable.
5. Structure Functions and PDF’s

SF is the description of the collection of point-like particles that forms nucleons while PDF’s provide momentum distributions of individual partons within the collection.

- Assuming parton model, n-N cross section can be rewritten in terms of point-like particle interactions

\[
\frac{d^2 \sigma^{\nu T}}{dx dy} = \frac{G_F^2 x_s}{\pi (1 + Q^2 / M_W^2)^2} \left[ q^{\nu T} (x) + (1 - y^2) q^{\bar{T}} + 2(1 - y) k^{\nu T} (x) \right]
\]

- Comparing the parton-neutrino to proton-neutrino SF and PDF’s are related as

\[
2x F_1^{\tilde{\nu} T} = 2 \left[ xq^{\tilde{\nu} T} (x) + xq^{\tilde{\nu} T} T (x) \right]
\]

\[
F_2^{\tilde{\nu} T} = 2 \left[ xq^{\tilde{\nu} T} T (x) + xq^{\tilde{\nu} T} T (x) + 2xk^{\tilde{\nu} T} T (x) \right]
\]

\[
x F_3^{\tilde{\nu} T} = 2 \left[ xq^{\tilde{\nu} T} T (x) - xq^{\tilde{\nu} T} T (x) \right]
\]

If no spin 0, 2xF1=F2
6. PDF Evolution: DGLAP Equations

The evolution equations by Dokshitzer-Gribov-Lipatov-Altarelli-Parisi provide mechanism to evolve PDF's to any kinematic regime or momentum scale, as a function of momentum transfer scale of the interactions.

\[
\frac{dG(x, M^2)}{d \ln M^2} = \frac{\alpha_s(\mu^2)}{2\pi} \int_x^1 \frac{dy}{y} \left[ q^S(y, M^2) P_{Gq}^s \left( \frac{x}{y} \right) + G(y, M^2) P_{GG} \left( \frac{x}{y} \right) \right]
\]

\(P_{ij}(x/y)\): Splitting function that is the probability of parton i with momentum y get resolved as parton j with momentum x<y

LO: \(O(\alpha_s)\)

NLO: \(O(\alpha_s^2)\)
7. How is $\sin^2 \theta_W$ measured?

- Cross section ratios between NC and CC proportional to $\sin^2 \theta_W$
- Llewellyn Smith Formula:

$$R^\nu (\bar{\nu}) = \frac{s^{\nu (\bar{\nu})}_{\text{NC}}}{s^{\nu (\bar{\nu})}_{\text{CC}}} = \sin^2 \theta_W \left( \frac{1}{2} - \frac{5}{9} \sin^4 \theta_W \right) \left( 1 + \frac{s^{\bar{\nu} (\nu)}_{\text{CC}}}{s^{\nu (\bar{\nu})}_{\text{CC}}} \right)$$

- Define experimental variable to distinguish NC and CC
- Compare the measured ratio with MC prediction
8-1. $\sin^2\theta_W$ Theoretical Uncertainty

- Significant correlated error from CC production of charm quark ($m_c$) modeled by slow rescaling mechanism

- Suggestion by Paschos-Wolfenstein by separating $\nu$ and $\bar{\nu}$ beams:

$$R^-=\frac{s_{NC}^\nu-s_{NC}^{\bar{\nu}}}{s_{CC}^\nu-s_{CC}^{\bar{\nu}}} = \sin^2\theta_W \left( \frac{1}{2} - \sin^2\theta_W \right) = \frac{R^\nu - R^{\bar{\nu}}}{1-r}$$

- Reduce charm CC production error by subtracting sea quark contributions
  - Only valence $u$, $d$, and $s$ contributes while sea quark contributions cancel out
  - Massive quark production through Cabbio suppressed $d_\nu$ quarks only
8-2. Experimental Uncertainties from $\nu_e$

- Electron neutrinos, $\nu_e$, in the beam fakes NC events from CC interactions
  - If the production cross section is well known, the effect will be smaller but since majority come from neutral K ($K^0$) whose x-sec is known only to 20%, this is a source of large experimental uncertainty
- Using tilted incident proton beam to eliminate neutral hadrons from the secondary beam.
9. Neutrino Oscillation & Its importance

- Caused by the fact that there are two different eigenstates for mass and weak flavors
- The weak eigenstates are expressed as a linear combination of mass eigenstates with time phase and mixing angle

- Neutrinos are one of the fundamental constituents in nature
  - Three weak eigenstates based on SM
- Left handed particles and right handed anti-particles only
  - Violates parity ➔ Why only neutrinos?
  - Is it because of its masslessness?
- SM based on massless neutrinos
- SM inconsistent
10. Atmospheric Neutrinos & Their Flux

- Neutrinos resulting from the atmospheric interactions of cosmic ray particles
  - He, p, etc + N \rightarrow \pi, K, etc
    - \pi \rightarrow \mu + \nu_\mu
    - \mu \rightarrow e + \nu_e + \nu_\mu
  - This reaction gives 2 \nu_\mu and 1 \nu_e

- Expected flux ratio between \nu_\mu and \nu_e is 2 to 1
- Give a predicted ratio of $\frac{N_{\nu_e}}{N_{\nu_\mu}} \approx \frac{1}{2}$
11. Importance of Zenith Angle

- The Zenith angle represents the different distance the neutrinos traveled through the earth.
- The dependence to the angle is a direct proof of the oscillation probability.

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 L}{E_e} \right)$$
Super-K Atmospheric Neutrino Results
12. Local Gauge Invariance

Physical meaning of local gauge invariance is the preservation of energy-momentum conservation and the physical law governing the interactions.

Requiring local gauge invariance forces the $L$ to accept new vector fields which are massless to preserve the invariance and introduces interactions between the vector field and the field currents.
Homework

• Presentation of detailed cuts used in data selection
  – Next Monday, Mar. 31