PHYS 5326 – Lecture #9 & 10

Friday, Feb. 21, 2003
Dr. Jae Yu

1. Interpretation of $\mathrm{Sin}^2\theta_W$ results
2. The link to Higgs
3. Neutrino Oscillation

•**Next makeup class is Friday, Mar. 14, 1-2:30pm, rm 200.**

SM Global Fits with New Results

Summer 2002

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-0.24
m_Z [GeV]	91.1875 ± 0.0021	0.00
Γ_Z [GeV]	2.4952 ± 0.0023	-0.41
σ^0_{had} [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.04
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.68
$A_l(P_\tau)$	0.1465 ± 0.0032	-0.55
R_b	0.21644 ± 0.00065	1.01
R_c	0.1718 ± 0.0031	-0.15
$A^{0,b}_{fb}$	0.0995 ± 0.0017	-2.62
$A^{0,c}_{fb}$	0.0713 ± 0.0036	-0.84
A_b	0.922 ± 0.020	-0.64
A_c	0.670 ± 0.026	0.06
A_l(SLD)	0.1513 ± 0.0021	1.46
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.87
m_W [GeV]	80.449 ± 0.034	1.62
Γ_W [GeV]	2.136 ± 0.069	0.62
m_t [GeV]	174.3 ± 5.1	0.00
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00
$Q_W(Cs)$	-72.18 ± 0.46	1.52

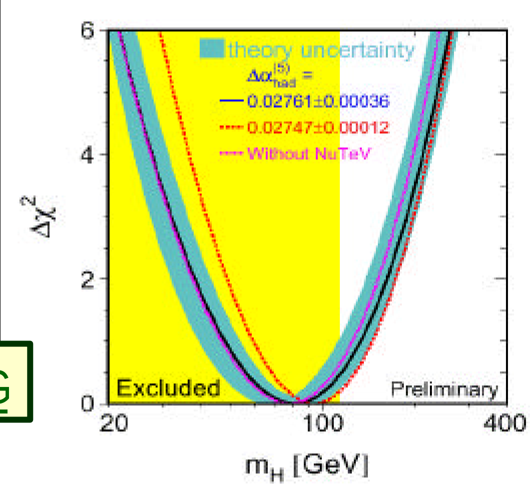
$(O^{meas}-O^{fit})/\sigma^{meas}$: -3 -2 -1 0 1 2 3

LEP EWWG: http://www.cern.ch/LEPEWWG

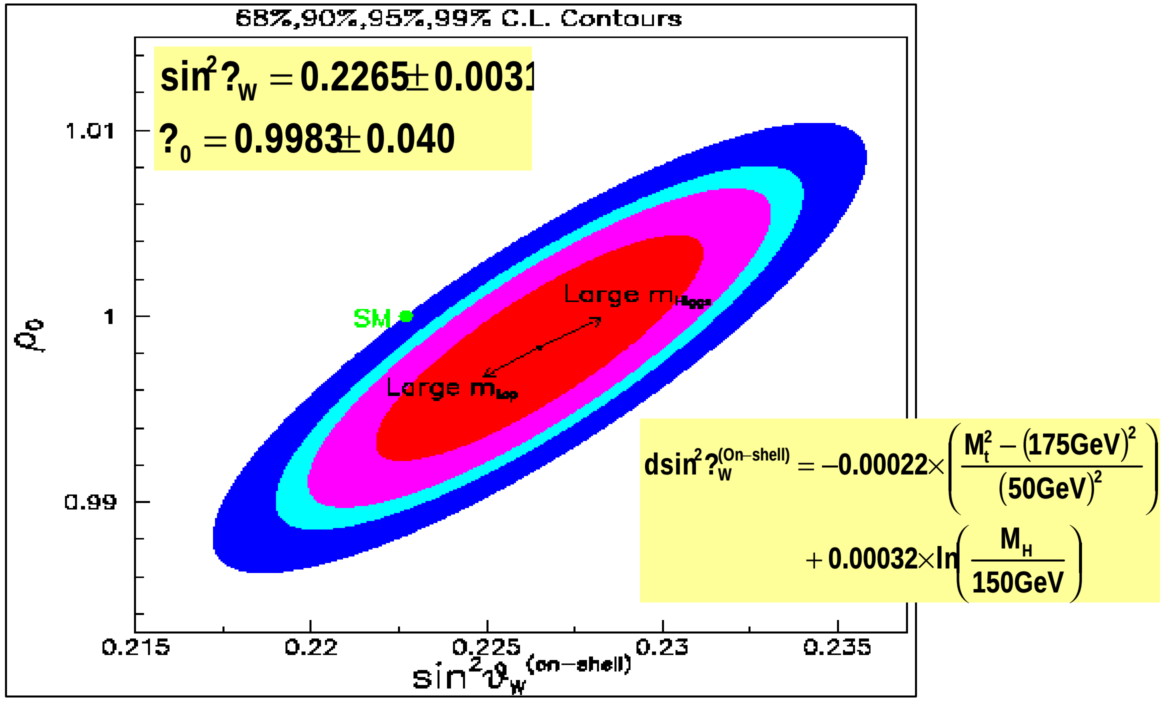
Without NuTeV
χ^2/dof=20.5/14: *P=11.4%*

With NuTeV
χ^2/dof=29.7/15: *P=1.3%*

Confidence level in upper M_{higgs} limit weakens slightly.



Tree-level Parameters: ρ_0 and $\sin^2\theta_W^{(on\text{-}shell)}$



- Either $\sin^2\theta_W^{(on\text{-}shell)}$ or ρ_0 could agree with SM but both agreeing simultaneously is unlikely

Model Independent Analysis

- $R^{\nu(\bar{\nu})}$ can be expressed in terms of quark couplings:

$$R^{n(\bar{n})} \equiv \frac{s\left(\overset{(-)}{n}\, N \to \overset{(-)}{n}\, X\right)}{s\left(\overset{(-)}{n}\, N \to \ell^{-(+)} X\right)} = g_L^2 + r^{(-1)} g_R^2$$

Where $$r \equiv \frac{s\left(\bar{?}N \to \ell^{+} X\right)}{s\left(?N \to \ell^{-(+)} X\right)} \approx \frac{1}{2}$$

Paschos-Wolfenstein formula can be expressed as

$$R^{-} = \frac{s_{NC}^{?} - s_{NC}^{\bar{?}}}{s_{CC}^{?} - s_{CC}^{\bar{?}}} = ?^2\left(\frac{1}{2} - \sin^2 ?_W\right) = \frac{R^{?} - rR^{\bar{?}}}{1-r} = g_L^2 - g_R^2$$

Model Independent Analysis

- Performed a fit to quark couplings (and g_L and g_R)
  - For isoscalar target, the νN couplings are

$$g_L^2 = u_L^2 + d_L^2 = ?_0^2\left(\frac{1}{2} - \sin^2 ?_W + \frac{5}{9}\sin^4 ?_W\right)$$

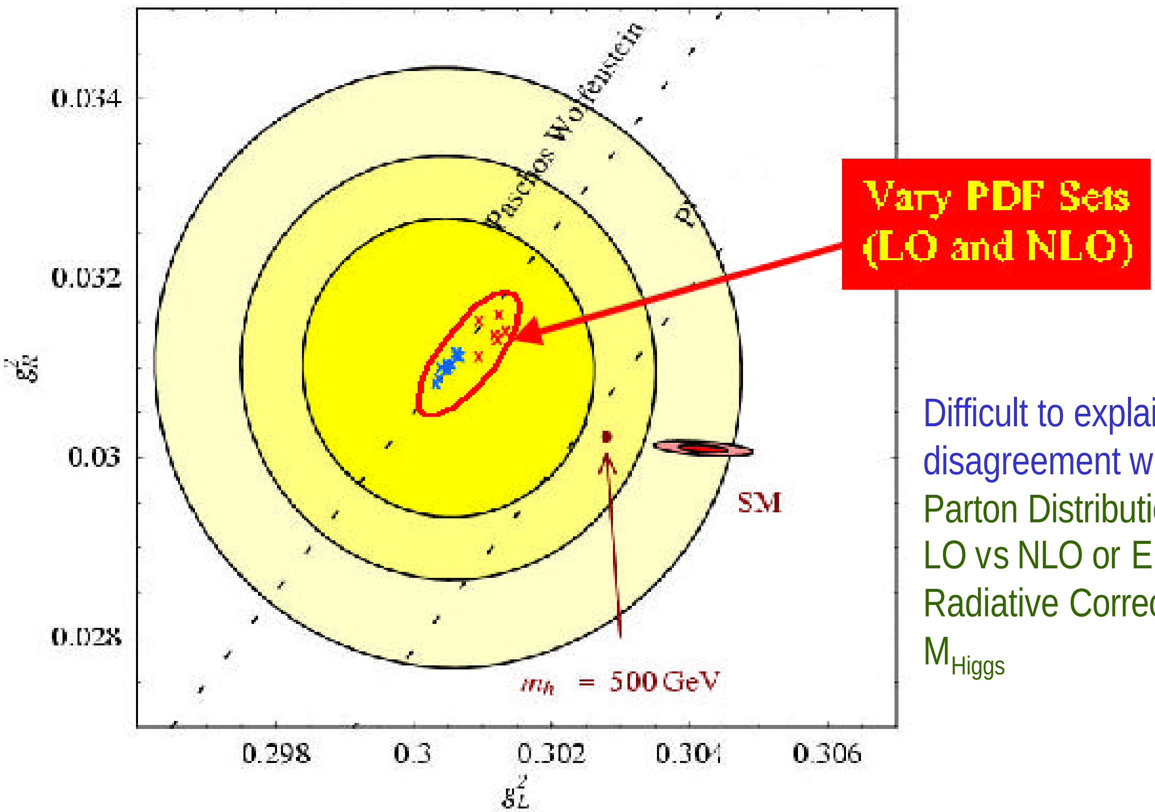
$$g_R^2 = u_R^2 + d_R^2 = ?_0^2 \frac{5}{9}\sin^4 ?_W$$

  - From two parameter fit to $\mathbf{R}_{n}^{\mathbf{exp}}$ and $\mathbf{R}_{\bar{n}}^{\mathbf{exp}}$

$$g_L^2 = 0.3005 \pm 0.0014$$ (SM: 0.3042 ← -2.6σ deviation)

$$g_R^2 = 0.0310 \pm 0.0011$$ (SM: 0.0301 ← Agreement)

Model Independent Analysis



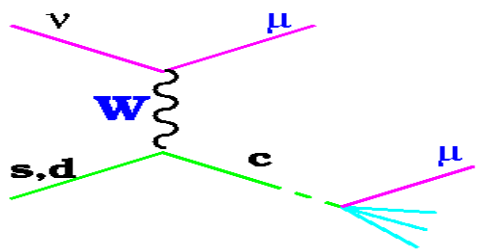
Difficult to explain the disagreement with SM by: Parton Distribution Function or LO vs NLO or Electroweak Radiative Correction: large M_{Higgs}

What is the discrepancy due to (Old Physics)?

- R^- technique is sensitive to q vs $\bar{q}$ differences and NLO effect
  - Difference in valence quark and anti-quark momentum fraction
- Isospin symmetry assumption might not be entirely correct
  - Expect violation about 1% ➔ NuTeV reduces this effect by using the ratio of ν and $\bar{\nu}$ cross sections ➔ Reducing dependence by a factor of 3

What is the discrepancy due to (Old Physics)?

- s vs $\bar{s}$ quark asymmetry
  - s and $\bar{s}$ needs to be the same but the momentum could differ
    - A value of $\Delta s = xs - x\bar{s} \sim +0.002$ could shift $\sin^2\theta_W$ by -0.0026, explaining ½ the discrepancy (S. Davison, et. al., hep-ph/0112302)
    - NuTeV di-μ measurement shows that $\Delta s \sim -0.0027 +/- 0.0013$



Use opposite sign di-μ events to measure s and $\bar{s}$.

What is the discrepancy due to (Old Physics)?

- NLO and PDF effects
  - PDF, m_c, Higher Twist effect, etc, are small changes
- Heavy vs light target PDF effect (Kovalenko et al., hep-ph/0207158)
  - Using PDF from light target on Iron target could make up the difference ➔ NuTeV result uses PDF extracted from CCFR (the same target)

$\nu_e \rightarrow \nu_s$ Oscillations with Large M_ν

- LSND result implicate a large Δm^2 (~10 — 100eV^2) solution for ν_e oscillation ➔MiniBooNe at FNAL is running to put the nail on the coffin
- How would this affect NuTeV $\sin^2\theta_W$?

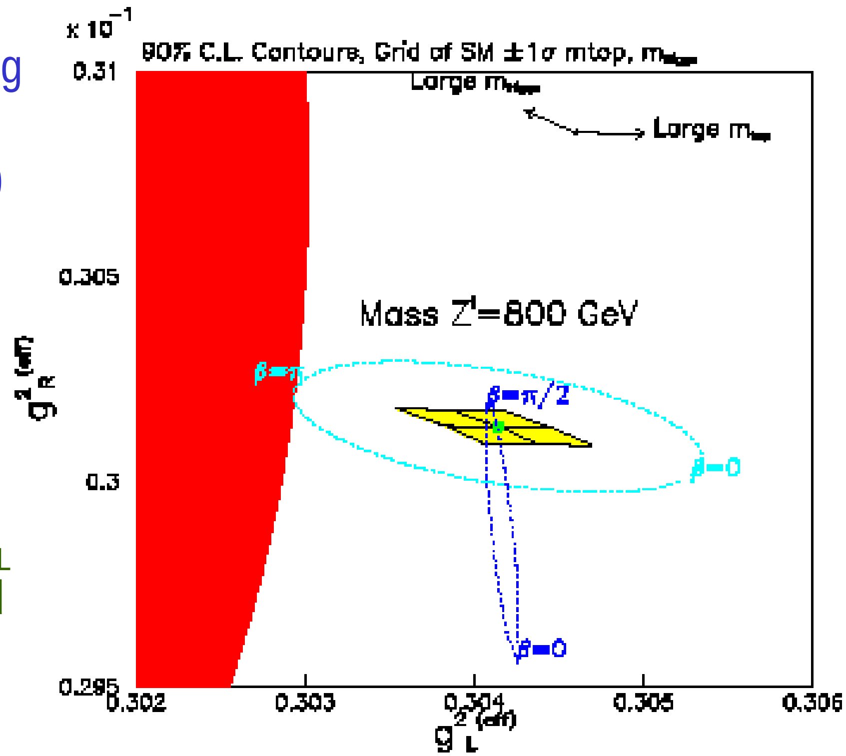
$$\sin^2 ?_W = \frac{1}{2} - \frac{R^{?} - rR^{\bar{?}}}{1 - r} \quad \text{and} \quad R^{n} = \frac{N^{n}_{Short} - N^{MC}_{n_e}}{N^{n}_{Long}}$$

If $\nu_e \rightarrow \nu_s$ with $P_{n_e \rightarrow n_s}$ then $N_{n_e} = N^{MC}_{n_e} P_{n_e \rightarrow n_e} = N^{MC}_{n_e}\left(1 - P_{n_e \rightarrow n_s}\right)$

Thus, MC will subtract more than it is in nature, causing measured R^ν to be smaller and thereby increasing $\sin^2\theta_W$

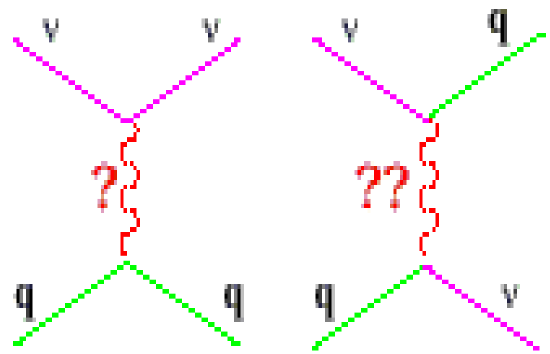
New Physics: Interactions from Extra U(1) – Z’

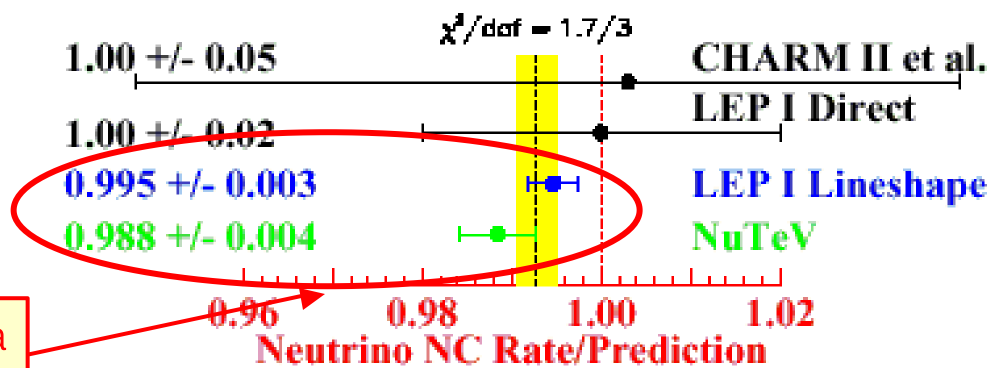
- Extra U(1) gauge group giving rise to interactions mediated by heavy Z’ boson ($M_{Z'} >> M_Z$)
- While couplings in these groups are arbitrary, E(6) gauge groups can provide mechanism for extra U(1) interaction via heavy Z’.
- Can give rise to g_R but not g_L which is strongly constrained by precision Z measurement



What other explanations (New Physics)?

- Heavy non-SM vector boson exchange: Z', LQ, etc
  – Suppressed $Z\nu\nu$ (invisible) coupling
  – LL coupling enhanced than LR needed for NuTeV





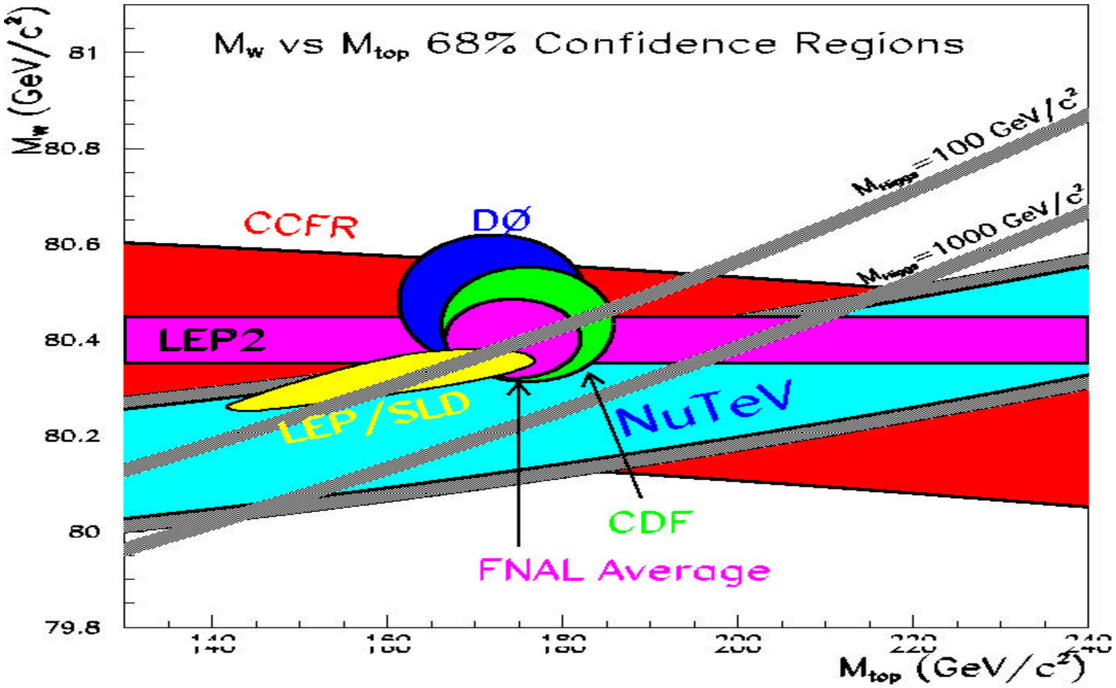
Both precision data are lower than SM

What other explanations (New Physics)?

- Propagator and coupling corrections
  - Small compared to the effect
- MSSM : Loop corrections wrong sign and small for the effect
- Many other attempts in progress but so far nothing seems to explain the NuTeV results
  - Lepto-quarks
  - Contact interactions with LL coupling (NuTeV wants m_Z~1.2TeV, CDF/DØ: m_Z>700GeV)
  - Almost sequential Z' with opposite coupling to ν

Langacker *et al*, Rev. Mod. Phys. **64** 87; Cho *et al.*, Nucl. Phys. **B531**, 65; Zppenfeld and Cheung, hep-ph/9810277; Davidson et al., hep-ph/0112302

Linking $\sin^2\theta_W$ with Higgs through M_{top} vs M_W



One-loop correction to $\sin^2\theta_W$

$$d\sin^2\theta_W^{(On-shell)} = -0.00022\times\left(\frac{M_t^2-(175GeV)^2}{(50GeV)^2}\right)+0.00032\times\ln\left(\frac{M_H}{150GeV}\right)$$

Neutrino Oscillation

- First suggestion of neutrino mixing by B. Pontecorvo at the K0, K0-bar mixing in 1957
- Solar neutrino deficit in 1969 by Ray Davis in Homestake Mine in SD. ➔ Called MSW effect
- Caused by the two different eigenstates for mass and weak
- Neutrinos change their flavor as they travel ➔ Neutrino flavor mixing
- Oscillation probability depends on
  - Distance between the source and the observation point
  - Energy of the neutrinos
  - Difference in square of the masses

Neutrino Oscillation Formalism

- Two neutrino mixing case:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

OR

$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$
$$|\nu_\mu\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

where $|\nu_e\rangle$ and $|\nu_\mu\rangle$ are weak eigenstates, while $|\nu_1\rangle$ and $|\nu_2\rangle$ are mass eigenstates, and θ is the mixing angle that give the extent of mass eigenstate mixture, analogous to Cabbio angle

Oscillation Probability

- Let ν_μ at time t=0 be the linear combination of ν_1 and ν_2 with masses m_1 and m_1, the wave function becomes:

$$\left|n_m(t=0)\right\rangle = -\sin q\left|n_1\right\rangle + \cos q\left|n_2\right\rangle$$

- Then later time t the ν_μ wave function becomes:

$$\left|n_m(t)\right\rangle = -\sin q\,\exp\left[-i\left(E_1/\hbar\right)t\right]\left|n_1\right\rangle + \cos q\,\exp\left[-i\left(E_2/\hbar\right)t\right]\left|n_2\right\rangle$$

- For relativistic neutrinos (E_ν>>m_i), the energies of the mass eigenstates are:

$$E_k = \sqrt{p^2 + m_k^2} \cong p + \frac{m_k^2}{2p}$$

Oscillation Probability

- Substituting the energies into the wave function:

$$\left|n_m(t)\right\rangle = \exp\left[-it\left(p + {m_1^2}/{2E_n}\right)\right]\left[-\sin q\left|n_1\right\rangle + \cos q\left|n_2\right\rangle \exp\left[{i\Delta m^2 t}/{2E_n}\right]\right]$$

where $\Delta m^2 \equiv m_1^2 - m_2^2$ and $E_n \cong p$.

- Since the ν's move at the speed of light, t=x/c, where x is the distance to the source of ν_μ.
- The probability for ν_μ with energy E_ν oscillates to ν_e at the distance *L* from the source becomes

$$\boxed{P(n_m \rightarrow n_e) = \sin^2 2q \sin^2\left(\frac{1.27\Delta m^2 L}{E_n}\right)}$$

Homework Assignments

- Produce an electron E_T spectrum of the highest E_T electrons in your samples
  – Due Wednesday, Feb. 26
- Complete the derivation of the probability for nm of energy E_ν to oscillate to ν_e at the distance *L* away from the source of ν_μ.
- Draw the oscillation probability distributions as a function of
  – Distance *L* for a fixed neutrino beam energy E_ν (=5, 50, 150 GeV)
  – E_ν for a detector at a distance *L* (=1.5, 735, 2200km) away from the source
- Due Wednesday, Mar. 5