CPT, Atmospheric Neutrinos and the MINOS Far Detector

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What does CPT mean for Neutrinos?

- In general any QFT which is local, Hermitian and Lorentz invariant is automatically CPT invariant
- Among other things, CPT requires that the mass of particles and anti-particles be equal
- The CPT implication for neutrino oscillation is $P_{\nu_\alpha \to \nu_\alpha} = P_{\overline{\nu}_\alpha \to \overline{\nu}_\alpha}$

Why should we look at CPT for Atmospheric Neutrinos?

- It has never really been done
- It probes "new physics"
- It will be a check to see if we understand the FD (*CPT is on very firm ground*)
- It can be practice for the CPT violation search that can be done when the beam is turned on

How can violation in CPT be searched for in Neutrinos ?

- A minimum of different two tests can be carried out by MINOS on the FD atmospheric neutrino data
- A standard (MACRO, Soudan II, Super-K) fit of the oscillation parameters done on positive and negative charged current neutrino events
- An asymmetry test

What atmospheric neutrinos should be used for a search?

- CC induced muons will be used because the sample of muons needed to test CPT must be reconstructed correctly and must be reconstructed with the proper charge determination
- For E > 1 GeV both these seems to be met. (See NuMI-L-436 for a sample study of these neutrinos and R.Lee WIW 2001 for charge reconstruction study)

Oscillation parameter fitting

- The MINOS FD atmospheric neutrinos data set could be broken into three separate data streams for CC muon events: Positive charge, Negative charge and Total
- Each of these data sets could then be put through independent fits to find $\sin^2(2\theta)$ and Δm^2
- These fit parameters can then be compared

Asymmetry Test

- An asymmetry test can be carried out by defining a parameter A_{CPT}
- $A_{CPT} = 0$ is the signal of CPT conservation
- However, the number of μ^+ and μ^- produced by CC interactions in the FD *are not equal even if* $A_{CPT} = 0$
- Several factors must be accounted for in order to get a proper asymmetry factor

A_{CPT}

$$A_{CPT} = \frac{\tilde{N}_+ - \tilde{N}_-}{\tilde{N}_+ + \tilde{N}_-}$$

$$\tilde{N}_+ = \sum_{i,j} \left(\frac{1}{P_{\nu_\mu \to \nu_\mu}(E_i, L_j)} \right)$$

$$\tilde{N}_- = \sum_{i,j} \left(\frac{1}{P_{\bar{\nu}_\mu \to \bar{\nu}_\mu}(E_i, L_j)} \right) R(E)$$

In this approach the N_+ and N_- are the number of muons corrected for the different oscillation probabilities. The data is binned in this approach. R(E) is correction factor that must be calculated.

A_{CPT} II

- R(E) must be simulated by MC. R(E) is a ratio which should change more slowly then the oscillation period of the neutrinos. Reducing the uncertainty in R will reduce the systematic error in A_{CPT}.
- The binning process also needs study as the number of muons are small and the bins either must be very coarse or the statistics will must be very low.

A possible test

- The simplest test is to replace $P(E_i,L_j)$ with the average $P(E_i,L_j)$ for both the neutrinos and anti-neutrinos. Then using the hypothesis the P is the same for neutrinos and anti-neutrinos calculate a value of A_{CPT} and see if it is consistent with $A_{CPT} = 0$.

What are the uncertainties and how well are they understood?

- Is the $\left(\sigma_{\nu_\mu} / \sigma_{\overline{\nu}_\mu}\right)_{CC}$ cross-section ratio understood?-Yes (~ 15 %, probably)
- Is the differences in the flux of neutrinos understood?-Yes (few %)
- Do we understand the energy resolution, angular resolution and charge determination capabilities of the detectors?- Yes

Matter Effects and Fake CPT Violation

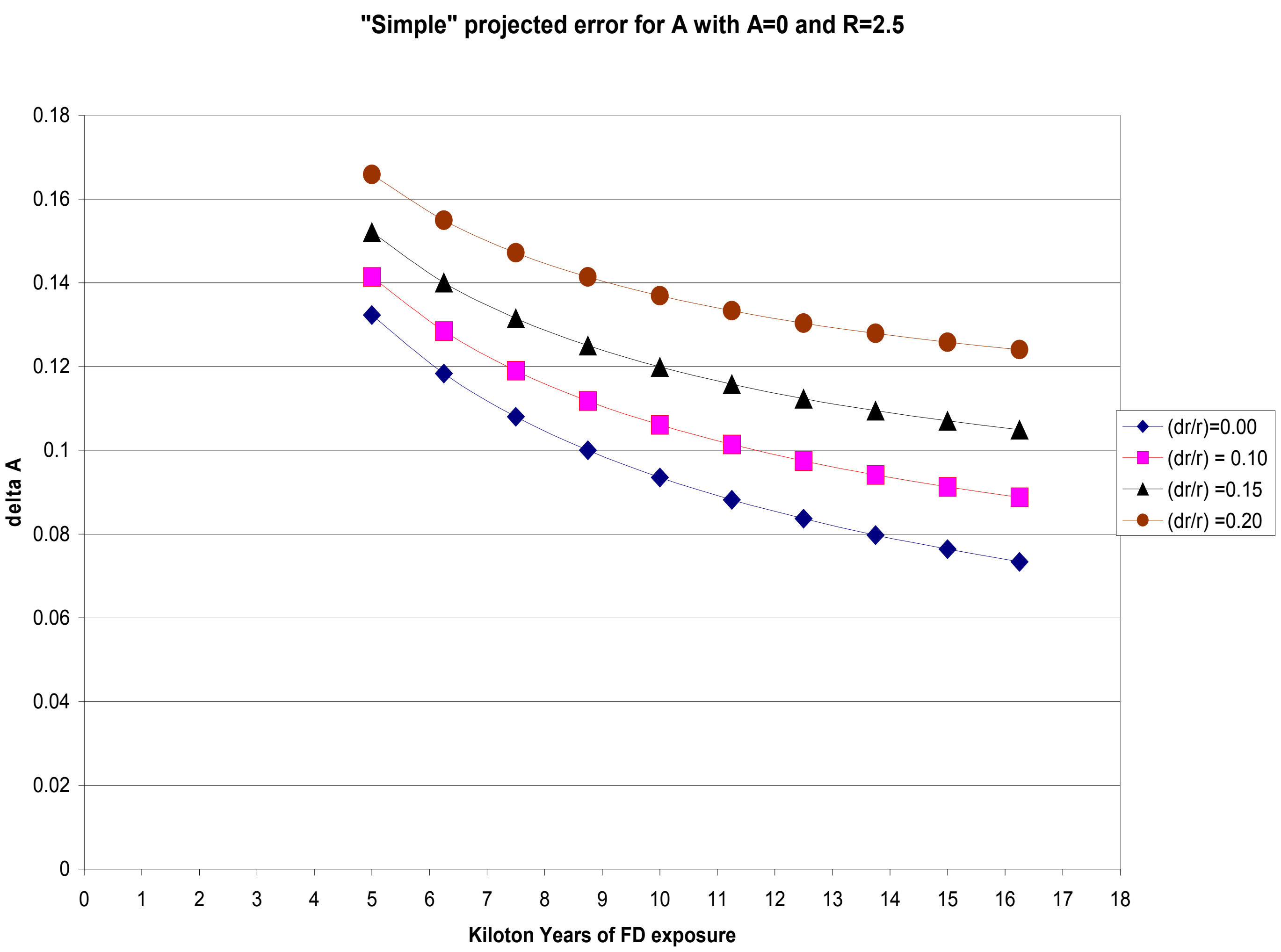
- Matter Effects (MSW effect) can give rise to asymmetry that looks like CPT violation.
- Exact predictions of this fake CPT violation vary author to author (it depends on phenomenological modeling of unknowns)
- However, it is probably alright to guess that it is small (less then 5 percent) and if it is much larger we will notice it

What limits exist on CPT violation in neutrinos?

- No direct limit exists (model independent)
- Work has been on looking at upward versus downward going muons. CPT violation might give rise to observable change in number of neutrinos observed in large non-magnetized detector. However, this is not direct since the sign of the charge is never determined for the muons.

What limit(s) can MINOS place on CPT violation in neutrinos?

- The expected flux of neutrino induced CC muon events in the FD of E > 1 GeV is ~20/k-t year (NuMI-L-436)
- ~ 70 % should be μ^+ (the cross section difference is the main reason this is not 1/2)
- The best technique to use and the actual limit we can reach are not know. Both will require MC and a understanding of FD
- *Any direct limit is an improvement*



"Simple" projected error for A with A=0 and R=2.5
delta A
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Kiloton Years of FD exposure
(dr/r)=0.00
(dr/r) = 0.10
(dr/r) =0.15
(dr/r) =0.20