Study of Neutrino-Antineutrino Transitions in MINOS

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Outline

- Introduction
- Discussion of the Model
- Overview of the MINOS Experiment
- Analysis Procedure
- Preliminary Results and Future Plans

Introduction

- Lorentz and CPT symmetry are inherent in Standard Model and General Theory of Relativity.
- Tiny violations of Lorentz and CPT symmetry might be observable in experiments and can lead to interesting phenomena.
- Lorentz and CPT violating couplings in the Standard Model Extension (SME) can describe neutrino-antineutrino oscillations.*

$$\nu_\mu \longrightarrow \bar{\nu}_\mu$$

- The aim of the present work is to study the probability of oscillation of muon neutrinos to muon antineutrinos and to find the sensitivity of MINOS to such oscillations.

*V. Alan Kostelecky and Matthew Mewes, PhysRevD.69, 016005 (2004)

*Sebastian Hollenberg, Octavian Micu, and Heinrich Päs, PhysRevD.80.053010 (2009)

The Model

- Considering two neutrino generations, the Schrodinger equation reads:

$$i\frac{d}{dt}\begin{pmatrix}\nu_\mu\\ \nu_\tau\\ \bar{\nu}_\mu\\ \bar{\nu}_\tau\end{pmatrix} = h_{eff}\begin{pmatrix}\nu_\mu\\ \nu_\tau\\ \bar{\nu}_\mu\\ \bar{\nu}_\tau\end{pmatrix}$$

- If we assume Lorentz and CPT violation, and consider a set of four coefficients b_μ, b_τ, $c_{\mu\mu}$, $c_{\tau\tau}$ which govern it, we can get neutrino-antineutrino oscillations, and as well as altered dispersion relations in the standard $\nu_\mu \rightarrow \nu_\tau$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$ sectors.

$$h_{eff} = diag\left(E + \frac{\sum m^2}{4E}\right) + \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta - \frac{C_{\mu\mu}}{2E} & \frac{\Delta m^2}{4E}\sin 2\theta & \frac{B_\mu}{2E} & 0 \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta - \frac{C_{\tau\tau}}{2E} & 0 & \frac{B_\tau}{2E} \\ \frac{B_\mu}{2E} & 0 & -\frac{\Delta m^2}{4E}\cos 2\theta - \frac{C_{\mu\mu}}{2E} & \frac{\Delta m^2}{4E}\sin 2\theta \\ 0 & \frac{B_\tau}{2E} & \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta - \frac{C_{\tau\tau}}{2E} \end{pmatrix}$$

$B_\mu(E) = b_\mu E^2$
$B_\tau(E) = b_\tau E^2$

$C_{\mu\mu}(E) = c_{\mu\mu} E^2$
$C_{\tau\tau}(E) = c_{\tau\tau} E^2$

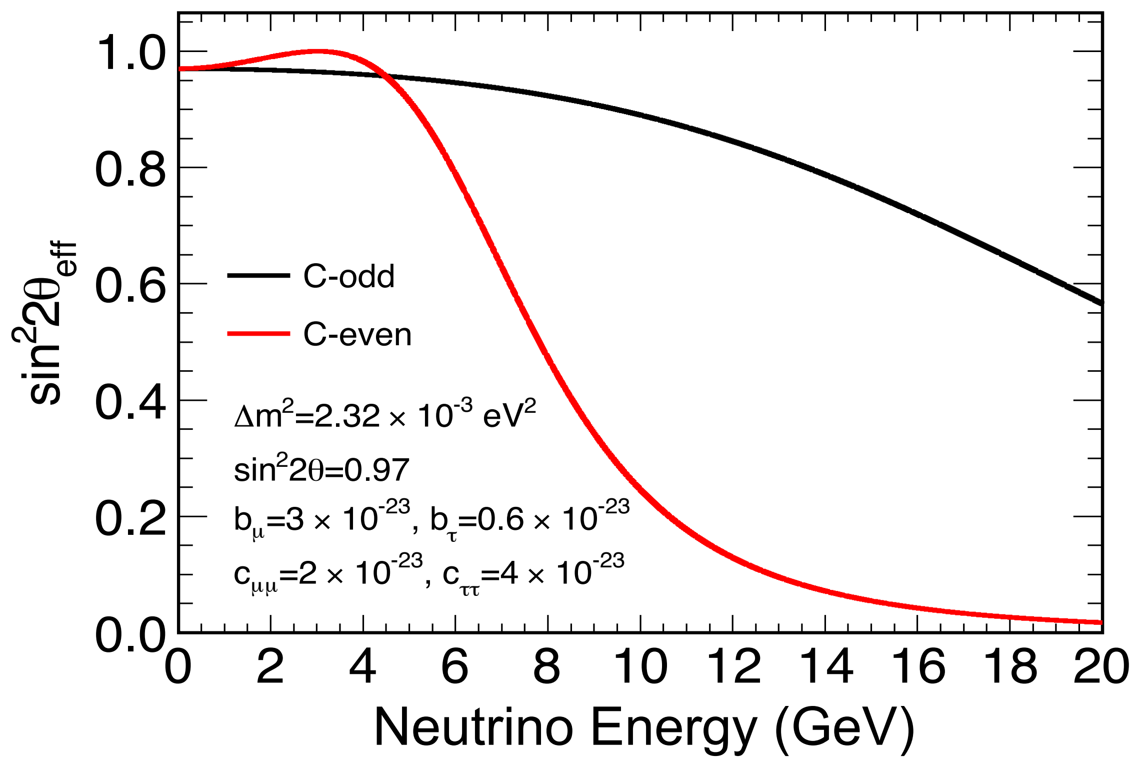
Resonant Mixing

- The effective hamiltonian can be diagonalised:

$$i\frac{d}{dt}\begin{pmatrix}\nu^-\\ \nu^+\end{pmatrix} = \begin{pmatrix} h_{\rm eff}^{C\text{-odd}} & 0 \\ 0 & h_{\rm eff}^{C\text{-even}}\end{pmatrix}\begin{pmatrix}\nu^-\\ \nu^+\end{pmatrix}.$$

$C\nu^- = -\nu^-$; C-odd states

$C\nu^+ = \nu^+$; C-even states

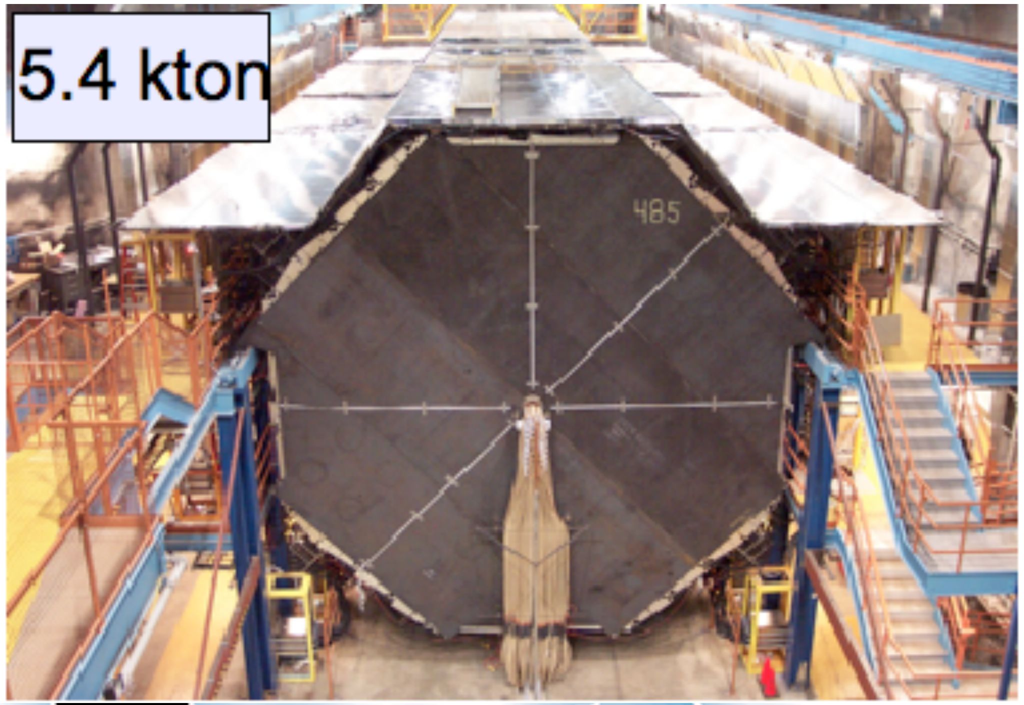


- For certain values of parameters b_μ, b_τ, $c_{\mu\mu}$, $c_{\tau\tau}$, resonant mixing for C-odd and C-even states occurs.

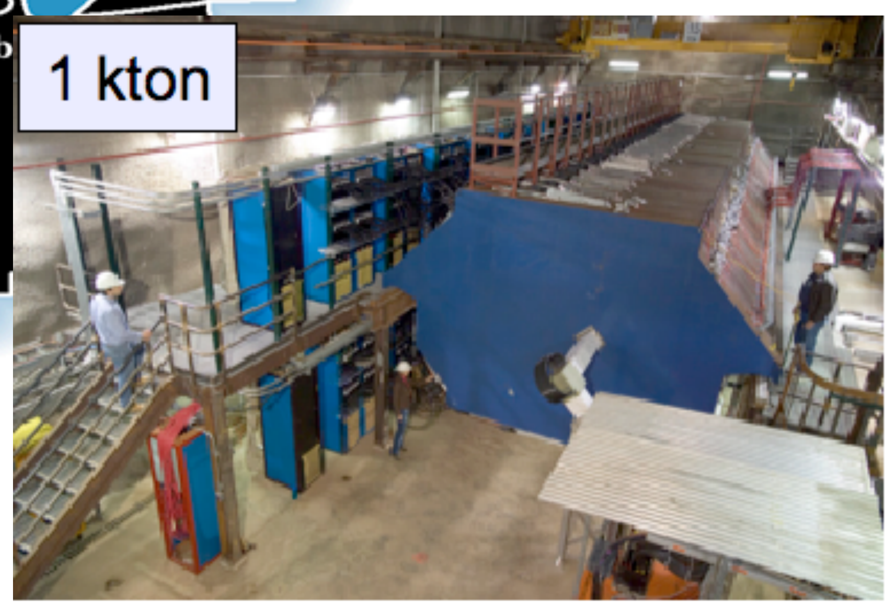
- The neutrino-antineutrino mixing occurs only between C-even states and C-odd states

- The condition for resonance needs to be satisfied.

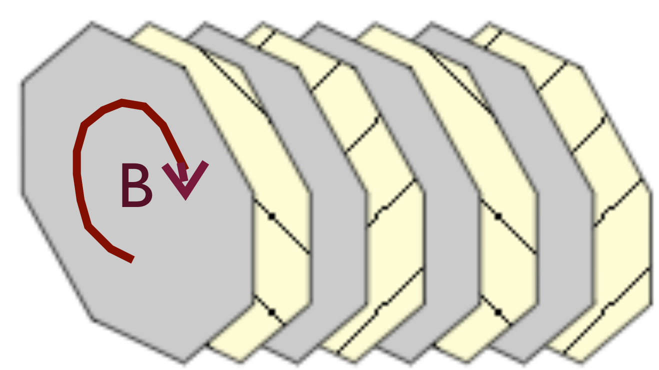
The MINOS Experiment



- NuMI high intensity neutrino beam at Fermilab (Average power ~340 kW)
- Near Detector:
  - 100m deep, 1 km from source.
  - Measure beam composition and energy spectrum.
- Far Detector:
  - 700m deep, 735 km from source.
  - Search for evidence of oscillations.



- Alternating layers of 2.54cm steel and 1cm plastic scintillator with WLS and clear fibre.
- ~1.3T magnetic field.

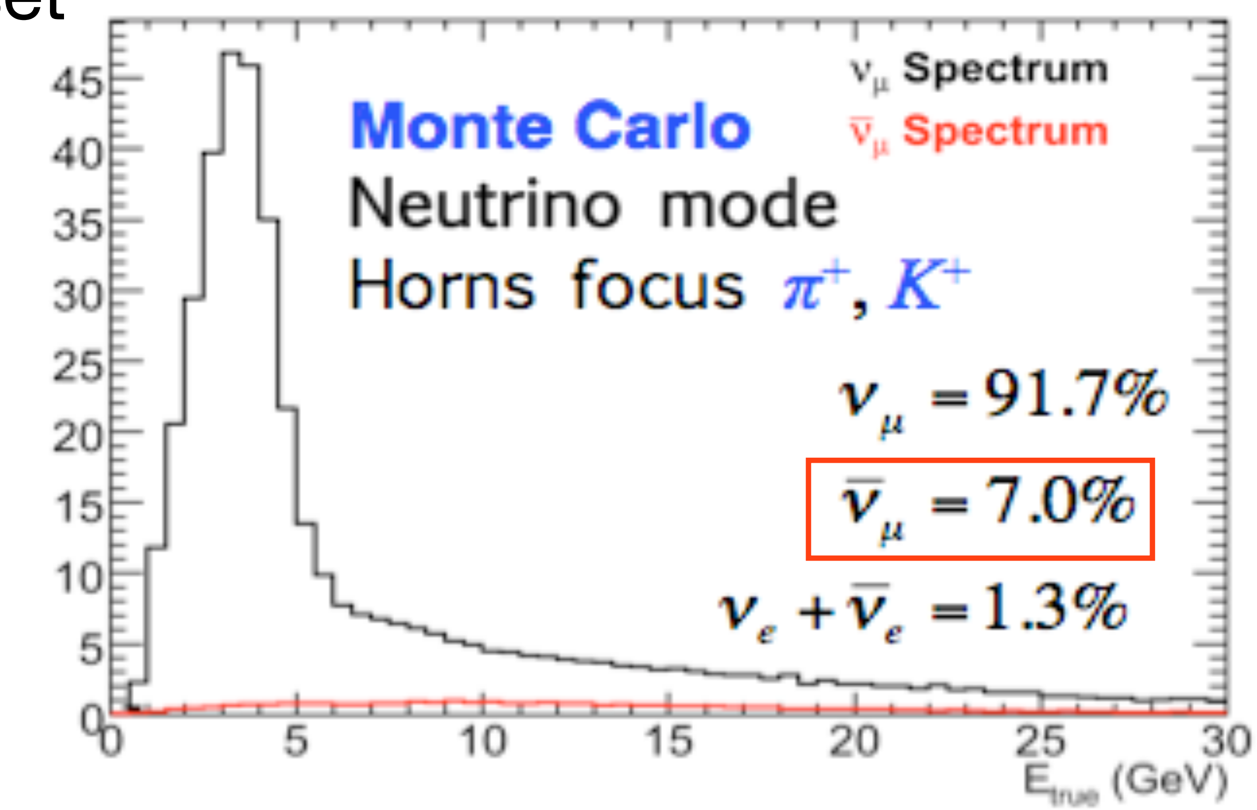


Data collected:

- 10.71×10^{20} POT (neutrino-optimised mode)
- 3.36×10^{20} POT (antineutrino-optimised mode)

Selecting Antineutrinos

- Used the neutrino-optimised MC dataset
  - 7% antineutrinos at the Far Detector.
  - Higher energy than neutrinos.



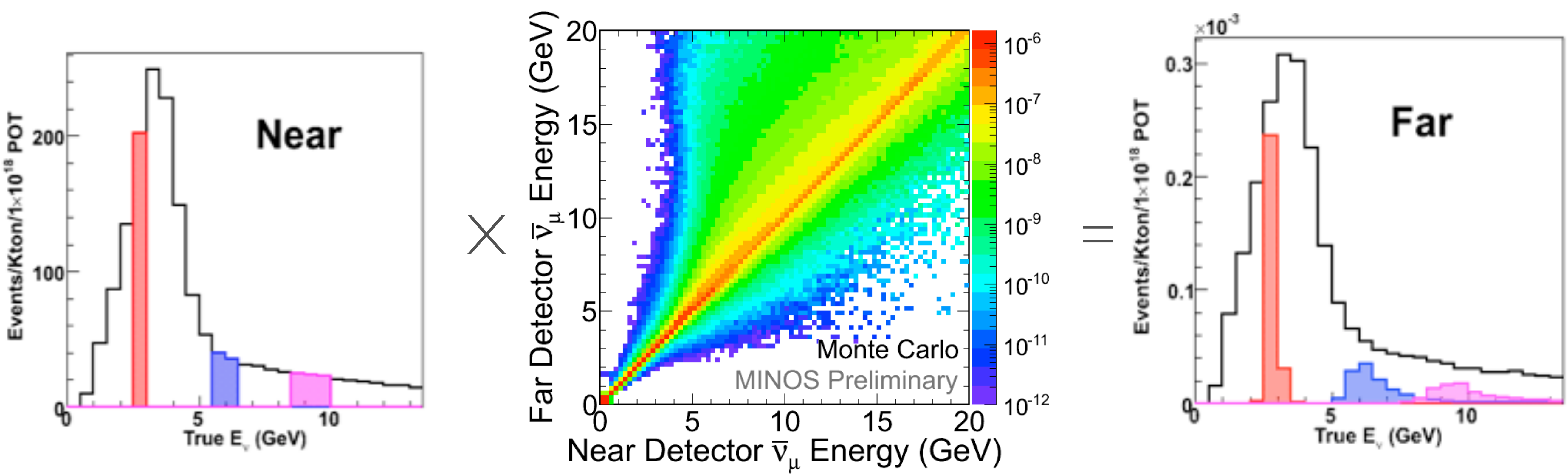
- Antineutrinos interact as:

$$\bar{\nu}_\mu + N \rightarrow \mu^+ + X$$

- Positively charged tracks with interaction vertex inside the detector.
- To reduce the misidentified NC and ν_μ CC background:
  - A discriminant variable - formed from 3 variables describing track properties.
  - Confidence of charge-sign determination from track fit.
  - Compare the track direction at the vertex to that at the end of the track.

Near To Far Extrapolation

- The ND spectrum is used to predict the FD spectrum.
- Flux and cross-section uncertainties cancel.
- Using the Matrix Method extrapolation framework adapted for antineutrino oscillation analysis.



Beam Matrix

Generating FD $\bar{\nu}_\mu$ Prediction

FD ν_μ → Oscillate with oscillation probability $P(\nu_\mu \rightarrow \bar{\nu}_\mu)$ → Efficiency Corrections → transitioned $\bar{\nu}_\mu$

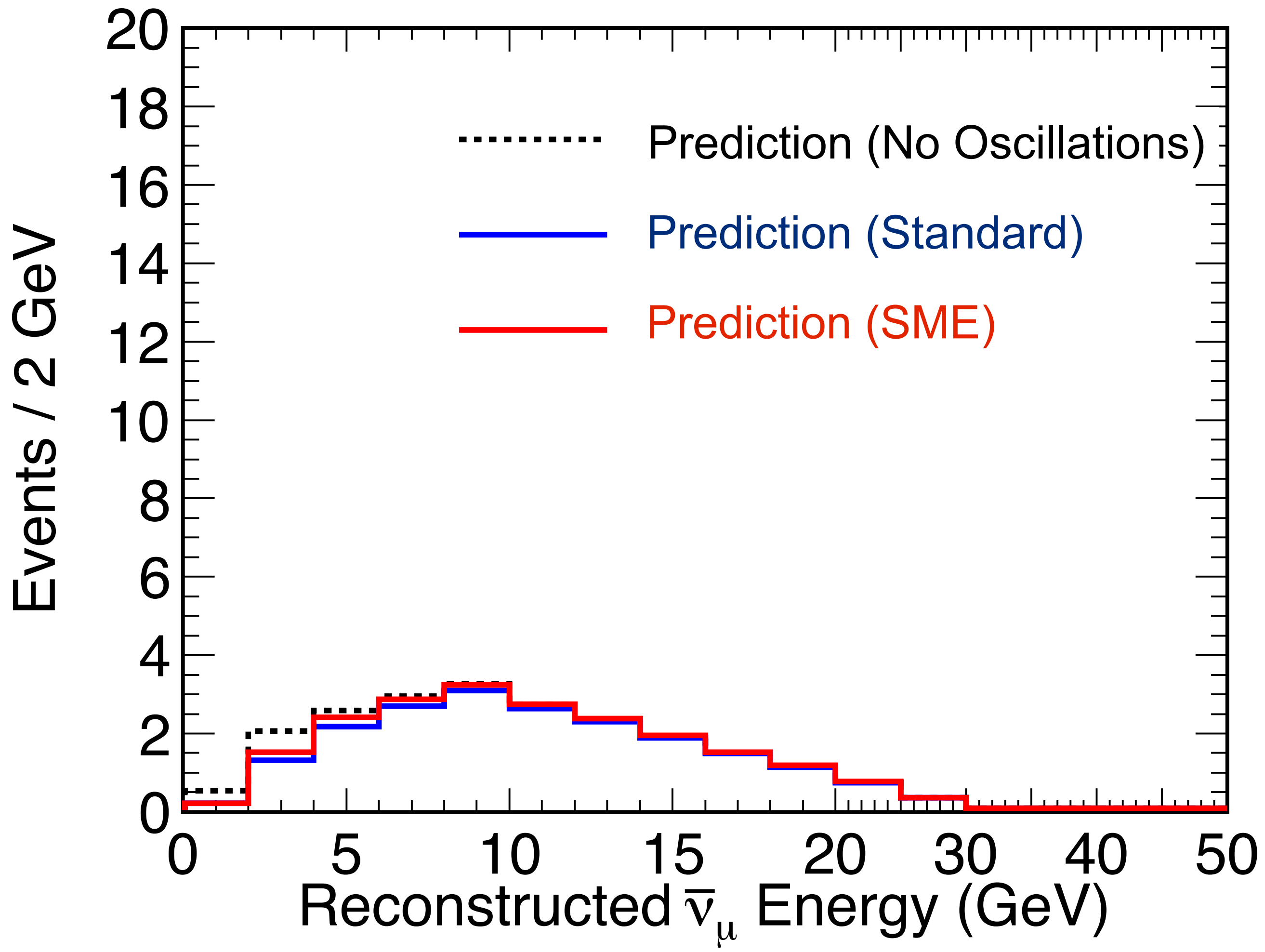
FD $\bar{\nu}_\mu$ → Oscillate with survival probability $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$ → Efficiency Corrections → $\bar{\nu}_\mu$

Add

\+ Add backgrounds → Far Detector $\bar{\nu}_\mu$ prediction

Far Detector $\bar{\nu}_\mu$ Prediction

- The Far Detector prediction is made using the following parameters:
  - $\Delta m^2=2.32\text{x}10^{-3}\ eV^2$, $\sin^2 2\theta=0.97$
  - $b_\mu=3\text{x}10^{-23}$, $b_\tau=0.6\text{x}10^{-23}$, $c_{\mu\mu}=2\text{x}10^{-23}$, $c_{\tau\tau}=4\text{x}10^{-23}$



Standard ⇒ 2 flavour ν_μ-ν_τ oscillation model

Far Detector $\overline{\nu}_\mu$ Prediction

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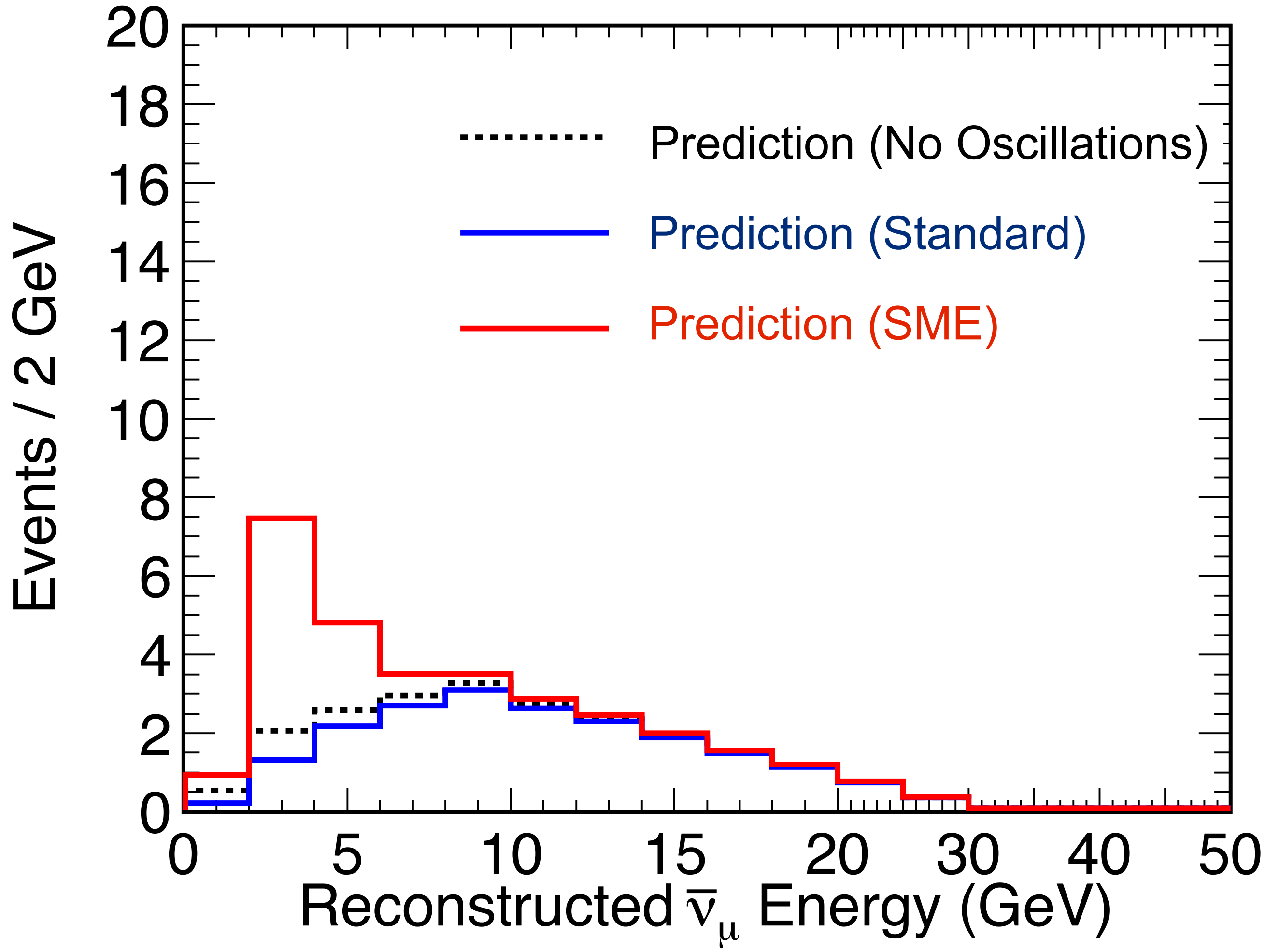

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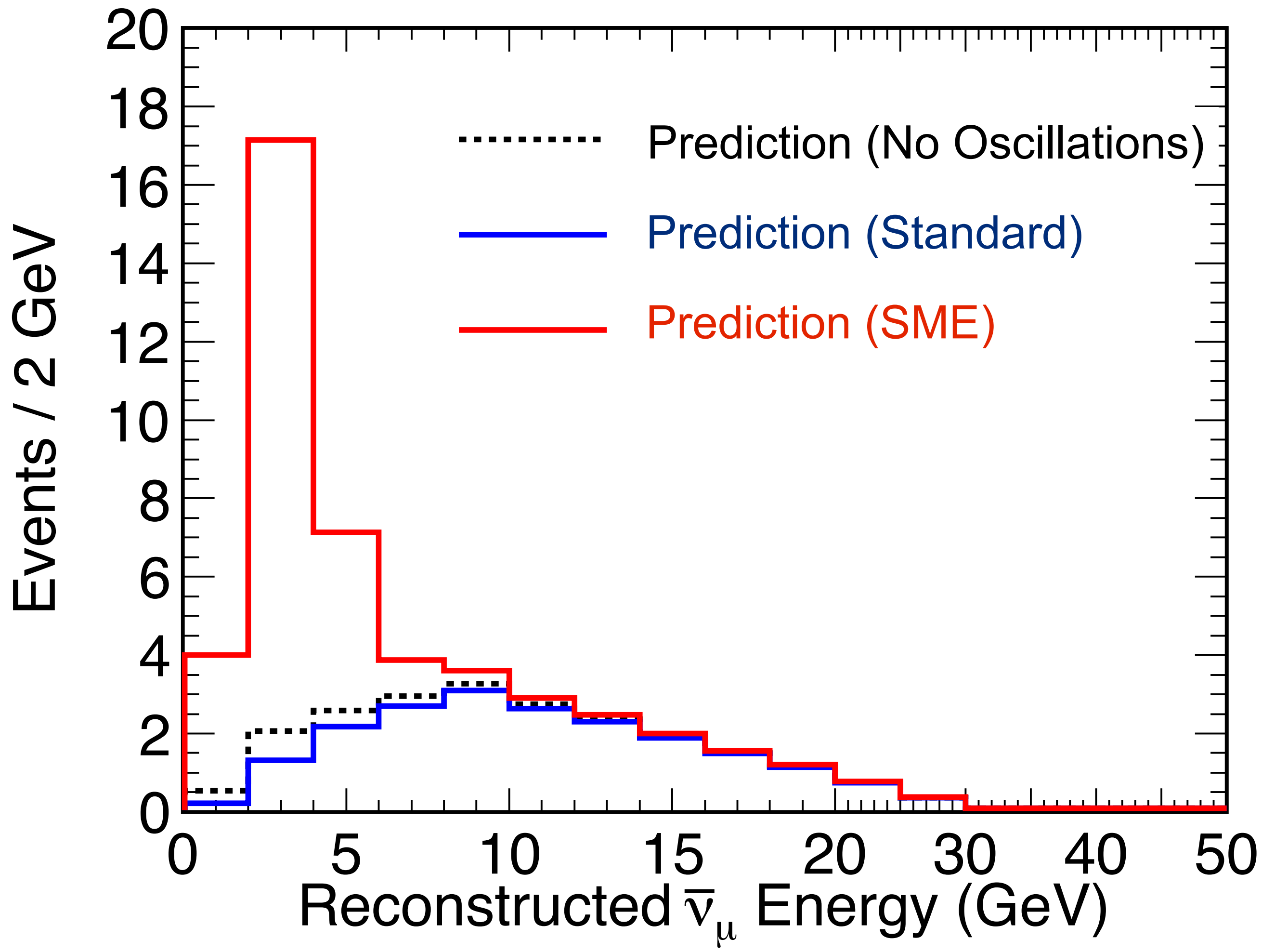

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Summary and Outlook

- Demonstrated that the ν_μ to $\overline{\nu}_\mu$ transitions are governed by the size of Lorentz and CPT violating parameters.
- It is possible to see the signal for such transitions in MINOS.
- Working towards obtaining the sensitivity of MINOS to transitions and to obtain the parameters b_μ, b_τ, $c_{\mu\mu}$, $c_{\tau\tau}$ that govern them.
- This would be the major part of my thesis. First analysis with this model.

- I have also worked on the analysis of the 7% $\overline{\nu}_\mu$ component in the 7.1×10^{20} POT neutrino-optimised data.
- This analysis excluded the $(3.37 < |\Delta\overline{m}^2| < 1000)\times10^{-3}$ eV^2 at 90% C.L., assuming $\sin^2 2\overline{\theta}=1$.
- The results have been published : P. Adamson et al. (MINOS Collaboration), **"Search for the disappearance of muon antineutrinos in the NuMI neutrino beam"**, Phys. Rev. D 84, 071103(R) (2011)

THANK YOU

BACKUP

Relation of b_μ, b_τ , $c_{\mu\mu}$ and $c_{\tau\tau}$ coefficients to more fundamental coefficients

The LV equations of motion can be written in analogy to the Dirac Equation:

$$(i\Gamma^\nu_{AB}\partial_\nu - M_{AB})\nu_B = 0,$$

where

$$\Gamma^\nu_{AB} = \gamma^\nu \delta_{AB} + c^{\mu\nu}_{AB}\gamma_\mu + d^{\mu\nu}_{AB}\gamma_5\gamma_\mu + e^\nu_{AB} + if^\nu_{AB} + \tfrac{1}{2}g^{\lambda\mu\nu}_{AB}\sigma_{\lambda\mu},$$

$$M_{AB} = m_{AB} + im_{5AB}\gamma_5 + a^\mu_{AB}\gamma_\mu + b^\mu_{AB}\gamma_5\gamma_\mu + \tfrac{1}{2}H^{\mu\nu}_{AB}\sigma_{\mu\nu}.$$

$c_{\mu\mu} = 2(c_L)^{TT}{}_{\mu\mu}\,[1+ \cos^2\Theta]$

$c_{\tau\tau} = 2(c_L)^{TT}{}_{\tau\tau}\,[1+ \cos^2\Theta]$

$b_\mu = -i \sin 2\Theta\ \tilde{g}^{ZT}{}_{\mu\bar{\mu}}$

$b_\tau = -i \sin 2\Theta\ \tilde{g}^{ZT}{}_{\tau\bar{\tau}}$

$c_L = c + d$

$\tilde{g}^{ZT} \equiv g^{0ZT} + (i/2)\epsilon^{0Z}{}_{\lambda\rho}\, g^{\lambda\rho T},$

Θ is the celestial colatitude

- Maximal experimental sensitivities attained for coefficients in the neutrino sector of minimal SME
- Experimental limits for $(c_L)^{TT}_{\mu\mu}$, $(c_L)^{TT}_{\tau\tau}$, $\tilde{g}^{ZT}_{\mu\bar{\mu}}$ and $\tilde{g}^{ZT}_{\tau\bar{\tau}}$ have not been obtained yet.

$d=4$	Coefficient	$e\mu$	$e\tau$	$\mu\tau$	Coefficient	$e\mu$	$e\tau$	$\mu\tau$
	$\mathrm{Re}\,(c_L)^{XY}$	10^{-21}	–	10^{-23}	$\mathrm{Im}\,(c_L)^{XY}$	10^{-21}	–	10^{-21}
	$\mathrm{Re}\,(c_L)^{XZ}$	10^{-21}	–	10^{-23}	$\mathrm{Im}\,(c_L)^{XZ}$	10^{-21}	–	10^{-21}
	$\mathrm{Re}\,(c_L)^{YZ}$	10^{-21}	–	10^{-23}	$\mathrm{Im}\,(c_L)^{YZ}$	10^{-21}	–	10^{-21}
	$\mathrm{Re}\,(c_L)^{XX}$	10^{-21}	–	10^{-23}	$\mathrm{Im}\,(c_L)^{XX}$	10^{-21}	–	10^{-21}
	$\mathrm{Re}\,(c_L)^{YY}$	10^{-21}	–	10^{-23}	$\mathrm{Im}\,(c_L)^{YY}$	10^{-21}	–	10^{-21}
	$\mathrm{Re}\,(c_L)^{ZZ}$	10^{-19}	–	–	$\mathrm{Im}\,(c_L)^{ZZ}$	–	–	–
	$\mathrm{Re}\,(c_L)^{TT}$	10^{-19}	–	–	$\mathrm{Im}\,(c_L)^{TT}$	–	–	–
	$\mathrm{Re}\,(c_L)^{TX}$	10^{-22}	–	10^{-27}	$\mathrm{Im}\,(c_L)^{TX}$	10^{-22}	–	10^{-22}
	$\mathrm{Re}\,(c_L)^{TY}$	10^{-22}	–	10^{-27}	$\mathrm{Im}\,(c_L)^{TY}$	10^{-22}	–	10^{-22}
	$\mathrm{Re}\,(c_L)^{TZ}$	10^{-20}	–	–	$\mathrm{Im}\,(c_L)^{TZ}$	–	–	–

$P(\nu_\mu \rightarrow \bar{\nu}_\mu)$

$$P(\nu_\mu \rightarrow \bar{\nu}_\mu) = \frac{1}{4} * \left[\left(1 - \sin^2 2\theta_{c\text{-}odd} \sin^2\left(\Delta m^2 \frac{L}{4E}\right)\right) + \left(1 - \sin^2 2\theta_{c\text{-}even} \sin^2\left(\Delta m^2 \frac{L}{4E}\right)\right)\right]$$
$$- \frac{1}{2} * \left[\cos^2\theta_{c\text{-}odd}\cos^2\theta_{c\text{-}even} + \sin^2\theta_{c\text{-}odd}\sin^2\theta_{c\text{-}even}\right.$$
$$+ \cos^2\theta_{c\text{-}odd}\sin^2\theta_{c\text{-}even}\cos\left(\Delta m^2\frac{L}{4E}\right)$$
$$\left. + \sin^2\theta_{c\text{-}odd}\cos^2\theta_{c\text{-}even}\cos\left(\Delta m^2\frac{L}{4E}\right)\right] = P(\bar{\nu}_\mu \rightarrow \nu_\mu)$$

The relation between the effective and the standard mixing angles for C-odd and C-even states is given by:

$$\tan 2\theta_{c\text{-}odd} = \frac{\Delta m^2 \sin 2\theta}{((b_\mu - b_\tau + c_{\mu\mu} - c_{\tau\tau})\, E^2 + \Delta m^2 \cos 2\theta)};$$

$$\tan 2\theta_{c\text{-}even} = \frac{\Delta m^2 \sin 2\theta}{((-b_\mu + b_\tau + c_{\mu\mu} - c_{\tau\tau})\, E^2 + \Delta m^2 \cos 2\theta)}$$

Modified probabilities

Standard:

- Δm^2=2.32x10^{-3} eV^2, $\sin^2 2\theta$=0.97
- b_μ=0, b_τ=0, $c_{\mu\mu}$=0, $c_{\tau\tau}$=0

New:

- Δm^2=2.32x10^{-3} eV^2, $\sin^2 2\theta$=0.97
- b_μ=3x10^{-21}, b_τ=0.6x10^{-21},$c_{\mu\mu}$=2x10^{-21}, $c_{\tau\tau}$=4x10^{-21}