Neutral Current Interactions in MINOS: A Search for Sterile Neutrinos

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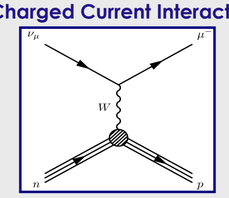
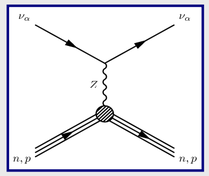
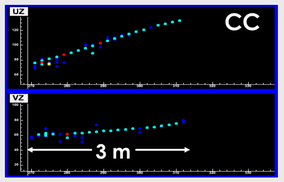
Neutrino Events in MINOS

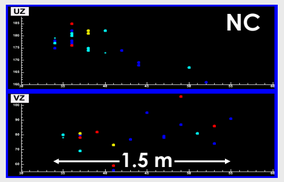
Charged Current Interaction



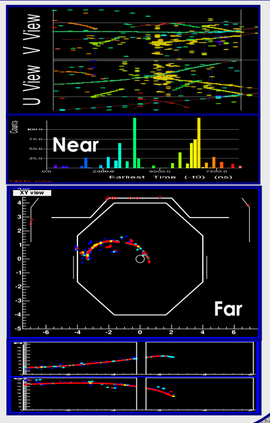
Neutral Current Interaction



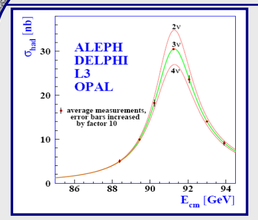




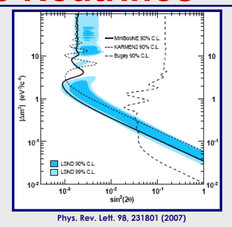
- Neutrino interactions occur in two types, charged current (CC) and neutral current (NC).
- In the MINOS detectors, a ν_μ CC event appears as a long muon track with hadronic activity at the vertex.
- NC events appear as short diffuse hadronic showers.
- Hadronic shower energy is determined from the amount of light produced in the scintillator.



Sterile Neutrinos



- Measurements of Z^0 width at LEP exclude more than 3 light active neutrinos.
- A 4th neutrino cannot couple to Z^0.
- Cannot participate in weak interactions → sterile neutrino



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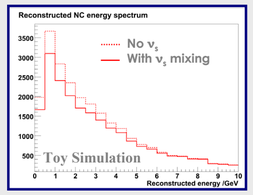
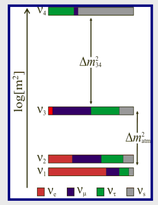
- LSND results suggested the existence of a fourth neutrino with large mass splitting.
- Earlier findings (Bugey, Karmen) combined with recent results from MiniBooNE strongly disfavour sterile neutrinos as an explanation for LSND.

- The total rate of NC events is unchanged by oscillations between 3 active neutrinos.
- If sterile neutrino mixing occurs, MINOS will observe a deficit in NC event rate.

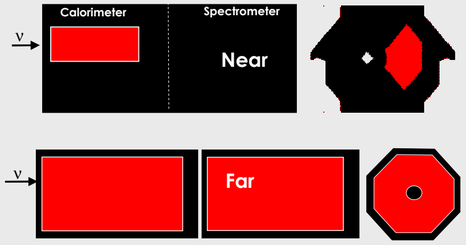


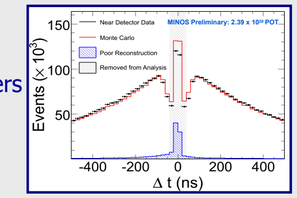


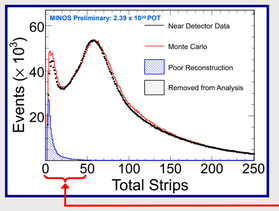
- If they exist, sterile neutrinos would
  - be possible dark matter candidates
  - indicate existence of one or more additional mass eigenstates
- **Sterile neutrinos → new physics!**

Event Pre-Selection Cuts

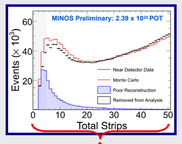
- Beam quality and detector quality cuts:
  - Beam positioning, magnetic horns energized, detector running within operational parameters
- Fiducial Volume cuts







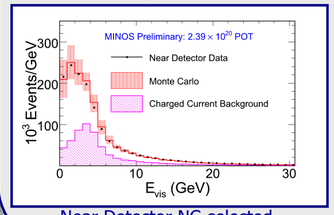
- High rate of neutrino interactions in Near Detector (ND) may cause reconstruction failures:
  - Split events from a single neutrino interaction
  - Event with vertex erroneously reconstructed inside fiducial volume
- Eliminate a large fraction using a series of cuts based on timing and topology.



Neutral Current Event Selection

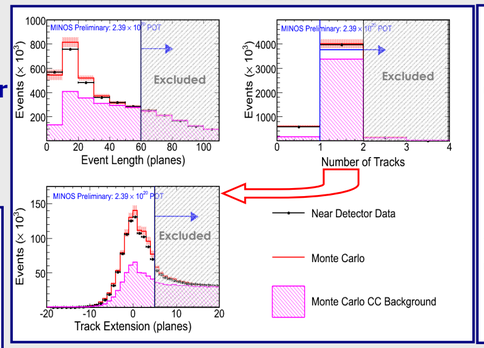
Event classified as NC-like if:

- Event length < 60 planes
- Has no reconstructed track **or**
- Has one reco'ed track that does not protrude more than 5 planes beyond the shower.



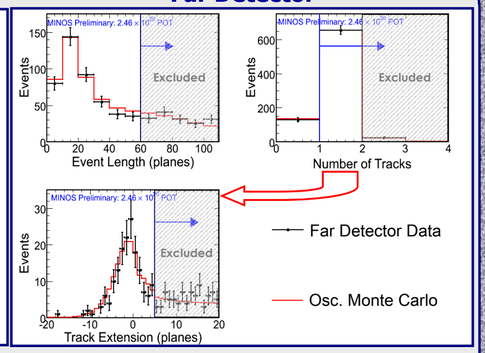
Near Detector NC-selected energy spectrum

Near Detector



- Error envelopes shown reflect systematic uncertainties due to cross-section modeling and beam modeling.

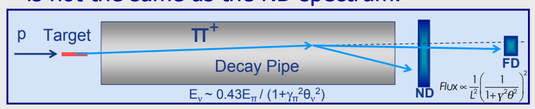
Far Detector



- MC oscillated with MINOS CC best fit: $\Delta m^2 = 2.38\times10^{-3}$ eV², $\sin^2(2\theta_{23})=1$

Sterile Neutrino Search with MINOS

- Unoscillated Far Detector (FD) energy spectrum is not the same as the ND spectrum.

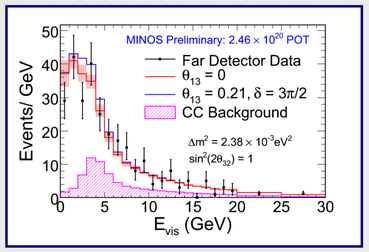


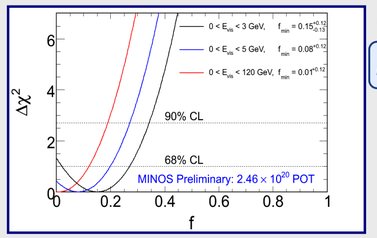
- Measured ND energy spectrum is used to predict the FD energy spectrum using the Far/Near Ratio method.

$$FD_i^{predicted} = \frac{FD_i^{MC}}{ND_i^{MC}} ND_i^{Data}$$

- Create a reconstructed energy vs. true energy 2D histogram from NC-selected events in FD.
- Oscillation weights are calculated for bins of true energy.
- For each bin of true energy, the reconstructed energy projection is multiplied by the corresponding oscillation weight.
- Prediction is obtained by multiplying each bin by ND_i^{Data}/ND_i^{MC}.

3-Flavour Measurement



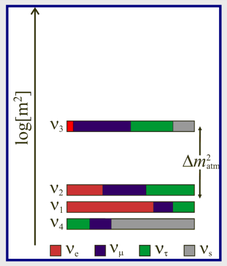


- CC Background is changed by oscillations between active neutrinos.
- For the 0-3 GeV reconstructed energy range, a 1.15σ deficit between Data and osc. Monte Carlo is observed.
- NC Disappearance Fraction

$$MC_{Pred} = NC_{Sig}(1-f) + CC_{Bg}$$

$$\chi^2 = \frac{(Data - MC_{Pred})^2}{MC_{Pred} + \sigma^2_{sys}}$$

For E_{vis} < 3 GeV: f < 0.35, 90% C.L.

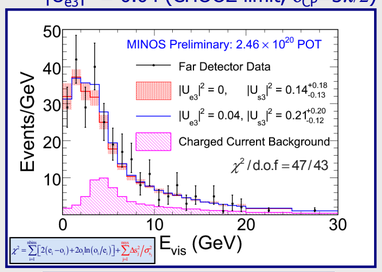


$$P_{\nu_\mu\to\nu_\mu} = 1 - 4|U_{\mu3}|^2\left(1-|U_{\mu3}|^2\right)\Delta^2_{31}$$
$$P_{\nu_\mu\to\nu_e} = 4|U_{\mu3}|^2|U_{e3}|^2\Delta^2_{31}$$
$$P_{\nu_\mu\to\nu_s} = 4|U_{\mu3}|^2|U_{s3}|^2\Delta^2_{31}$$
$$P_{\nu_\mu\to\nu_\tau} = 1 - P_{\nu_\mu\to\nu_\mu} - P_{\nu_\mu\to\nu_e} - P_{\nu_\mu\to\nu_s}$$

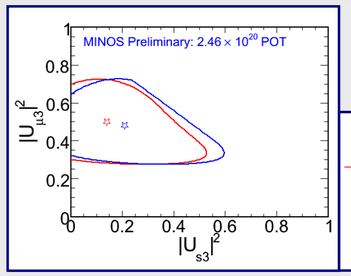
$$\sin^2 2\theta_{23} \leftrightarrow 4|U_{\mu3}|^2\left(1-|U_{\mu3}|^2\right)$$
$$\Delta^2_{31} = \sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)$$

4-Flavour Measurement

- Assume $\Delta m^2_{41} = 0$
  - Oscillation at single mass scale
- Fit for Δm^2_{31}, $|U_{\mu3}|^2$ and $|U_{s3}|^2$
- Fix $|U_{e3}|^2 = 0$
  $|U_{e3}|^2 = 0.04$ (CHOOZ limit, $\delta_{CP}=3\pi/2$)

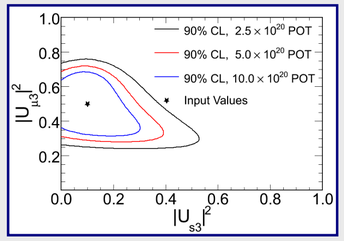


$$|U_{s3}|^2 = 0.14^{+0.18}_{-0.13}, \quad \text{for } |U_{e3}|^2 = 0$$
$$|U_{s3}|^2 = 0.21^{+0.20}_{-0.12}, \quad \text{for } |U_{e3}|^2 = 0.04$$



Far Detector	$\Delta_{41} = 0$
$|U_{e3}|^2 = 0$	$|U_{e3}|^2 = 0.04$
$|U_{\mu3}|^2 = 0.50^{+0.16}_{-0.15}$	$|U_{\mu3}|^2 = 0.48^{+0.18}_{-0.12}$
$|U_{s3}|^2 = 0.14^{+0.18}_{-0.13}$	$|U_{s3}|^2 = 0.21^{+0.20}_{-0.12}$

- 90% C.L. contours for the fits to $|U_{\mu3}|^2$ and $|U_{s3}|^2$



- 90% C.L. sensitivity curves for different NuMI beam exposures
- Limit on $|U_{s3}|^2$ will improve significantly as more data is collected.

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