MINOS Sensitivity to Non-Standard Interactions (NSI) using ν_e Appearance Events

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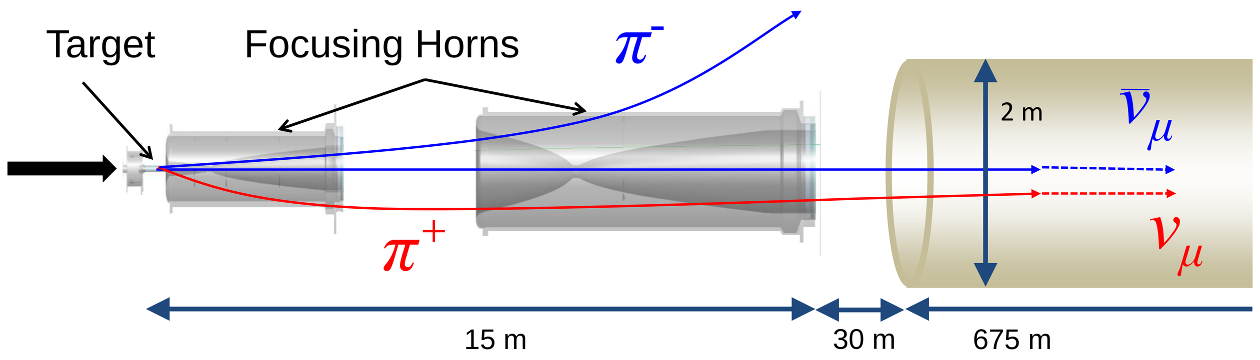
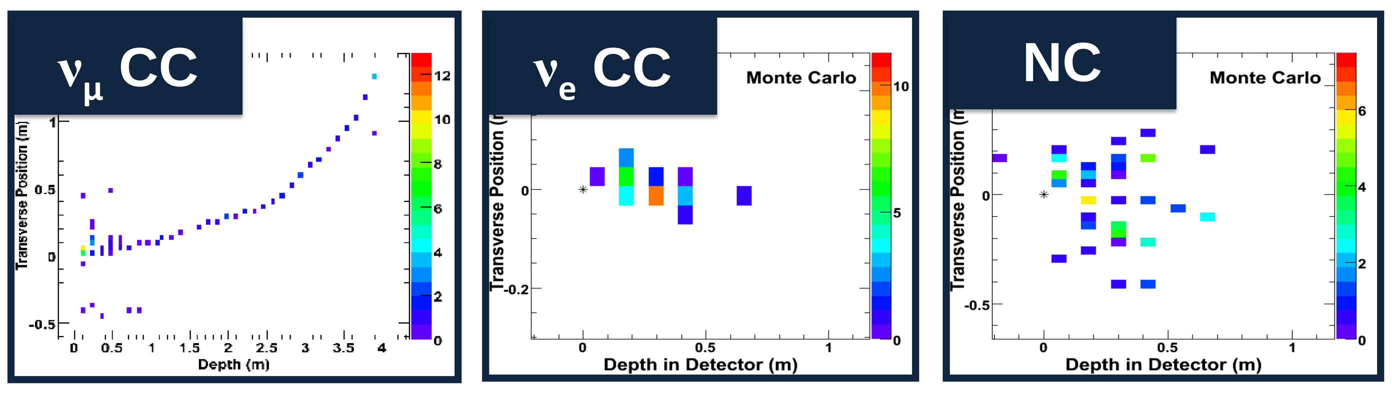
The MINOS Experiment, Electron Neutrino Appearance, and NSI

- **MINOS is an on-axis, long-baseline neutrino oscillation experiment, studying neutrinos from the FNAL NuMI beam**
- **Two functionally identical detectors**
  - **Near Detector:** 0.029 / 1.0 kT fiducial / total mass:
    - **Unoscillated neutrino spectrum assumed**
    - **Used to predict unoscillated result at Far Det.**
  - **Far Detector:** 4.0 / 5.4 kT fiducial / total mass at depth of 705m (2070 mwe):
    - **Observes oscillated neutrino spectrum**
  - Functional equivalence: cancels out systematic effects such as flux mismodeling and cross-section uncertainties to first order
- **NuMI beamline:** 120 GeV protons from Main Injector collide with graphite target to produce hadrons (mostly pions and kaons)
  - Charged hadrons decay to form muon neutrino beam
  - Magnetic horn focuses particles of specified charge to produce either a **neutrino-mode** or **antineutrino-mode** beam





- **MINOS capable of observing $\nu_\mu \rightarrow \nu_e$ oscillation**
  - Allowed MINOS to place limits on the value of θ_{13}:

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2(1.27\Delta m^2 L/E)$$

  - MINOS measurement dependent on $\mathbf{\sin^2(\theta_{23})}$, $\boldsymbol{\delta_{CP}}$, and the **mass hierarchy**
  - ❖ **MINOS 2013 results* offered a first glimpse at δ_{CP}**
- **The impact of non-standard interaction parameters**
  - NSI parameters introduce changes to the Hamiltonian analogous to standard matter effects

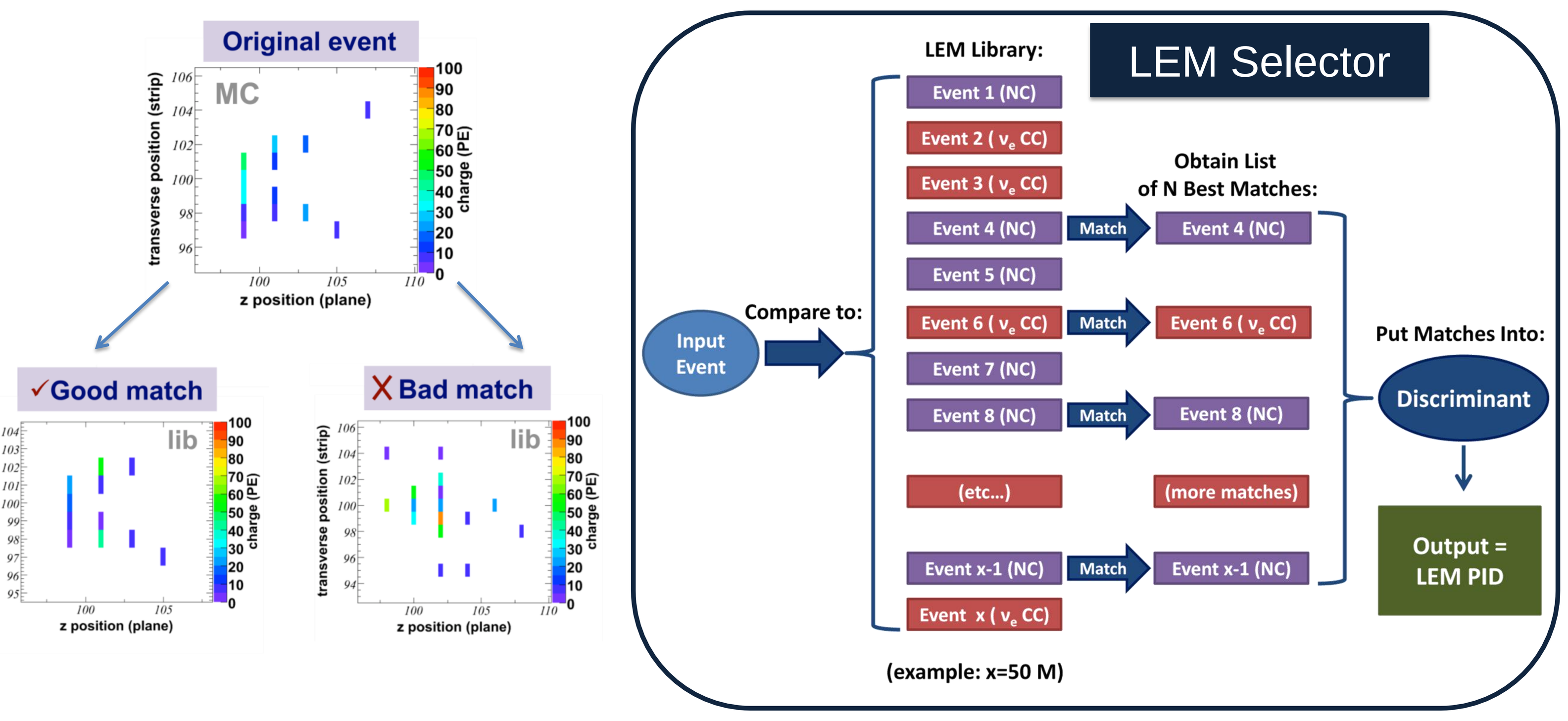
$$H = U_{PMNS}\begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m_{21}^2}{2E} & 0 \\ 0 & 0 & \frac{\Delta m_{31}^2}{2E} \end{bmatrix} U_{PMNS}^\dagger + \sqrt{2}G_F n_e \begin{bmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{bmatrix}$$

  - Represents physics beyond the Standard Model
  - $\nu_\mu \rightarrow \nu_e$ channel is sensitive to the $\varepsilon_{e\tau}$, $\delta_{e\tau}$ + δ_{CP} parameter space
  - **MINOS is sensitive to new physics!**

* Electron neutrino and antineutrino appearance in the full MINOS data sample, P. Adamson et al. (MINOS), Phys. Rev. Lett. 110 (2013) 171801, arXiv:1108.0015.

The MINOS Analysis

- **Implementation of NSI functions into appearance analysis framework**
  - Oscillation probability functions with NSI parameters incorporated
    - Migrated from channel-by-channel approximation to direct Hamiltonian probability calculation
  - Log-likelihood 2D grid search functions introduced to perform sweep over $\varepsilon_{e\tau}$, $\delta_{e\tau}$ + δ_{CP} parameter space



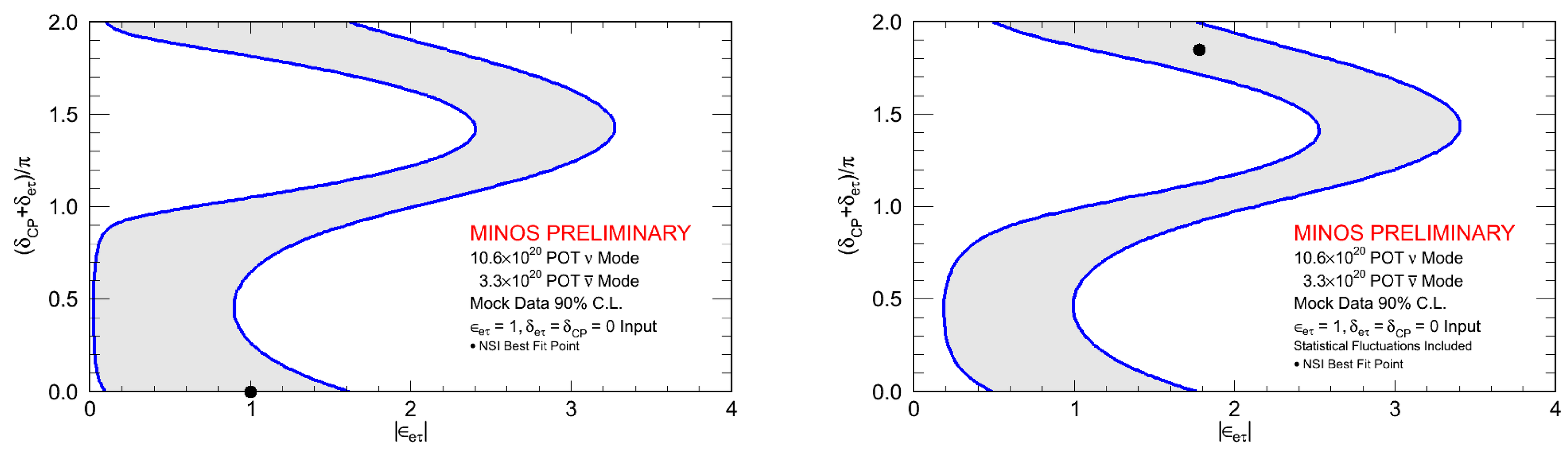
- **Make use of the Library Event Matching selector from the 2013 analysis to select events**
  - Simulate library of 20M Signal + 30M Neutral Current Far Det. MC events
    - Two separate libraries / selectors for neutrino and antineutrino
  - Compare candidate event to library and select a list of 50 best matches
  - Feed information from these best matches into a neural network discriminant
  - LEM uses raw hit information to avoid losses from variable construction
- **Make the Far Detector Prediction**
  - Apply LEM selection to Near Detector Data
  - Use a data-based algorithm to break up the various background selections
    - Different beam kinematics and oscillation for each background type
  - Use the Far/Near ratios from MC to turn each component to a **Far Detector Prediction:**

$$\mathrm{Far}_\alpha^{\mathrm{Predicted}}(n) = \mathrm{Near}_\alpha^{\mathrm{Data}}(n)\frac{\mathrm{Far}_\alpha^{\mathrm{MC}}(n)}{\mathrm{Near}_\alpha^{\mathrm{MC}}(n)}$$

- **Perform a shape fit of the combined neutrino + antineutrino data or Monte Carlo using the NSI oscillation framework**
  - Fit is performed over 3 bins of the selection variable and 5 bins of reconstructed energy
  - Input from the Far Detector prediction generates preliminary sensitivities
  - Input from the MINOS data produces limits upon the parameter space

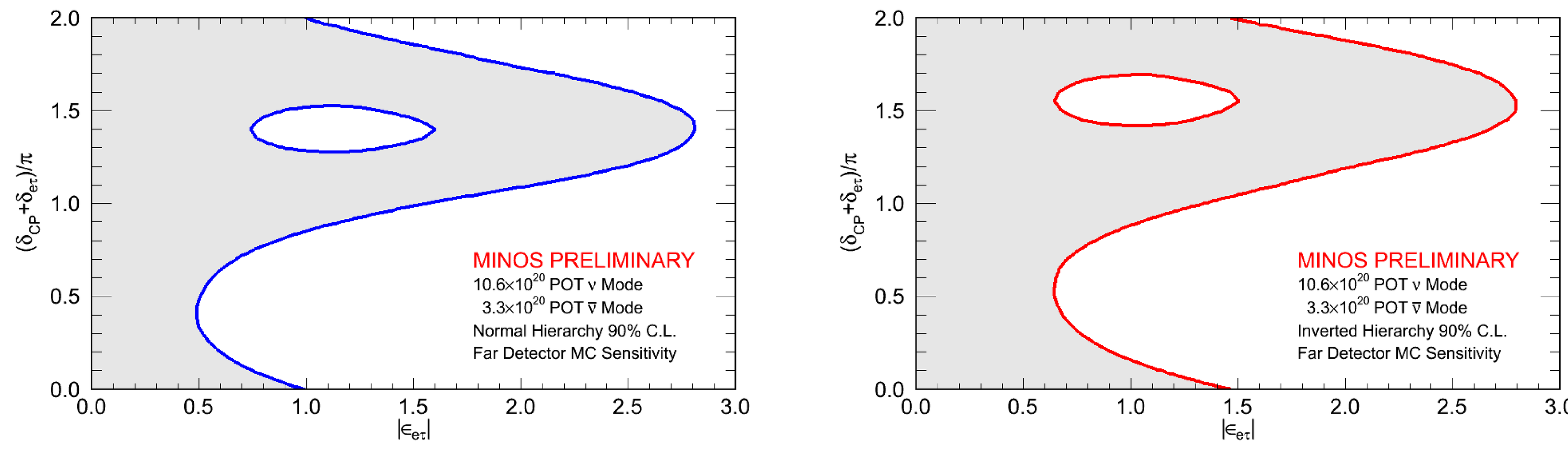
Validation and Sensitivities

- **Validation of the oscillation framework**
  - Reproduced upper 90% C.L. $\sin^2(2\theta_{13})$ sensitivity contour with new oscillation framework and NSI parameters defined as zero as consistency check
- **Validation of the fitting framework**
  - To verify performance of the NSI framework, two sets of mock data were generated:
    - Prediction made with $\varepsilon_{e\tau}$ =1.0, $\delta_{e\tau}$ = δ_{CP} = 0.0
    - Statistical fluctuations added to the $\varepsilon_{e\tau}$ =1.0, $\delta_{e\tau}$ = δ_{CP} = 0.0 prediction
  - Chosen best fit point contained in both tests, and marginal shifts in contour shape



- **Monte Carlo driven sensitivities**
  - 90% C.L. contours (-2ΔlnL = 4.61) shown for each mass hierarchy
  - Marginalized over four values of δ_{CP} with fixed set of standard oscillation parameters assumed

Parameter	Value
θ_{12}	0.600
θ_{13}	0.159
θ_{23}	0.785
Δm^2_{21}	7.59e-5
$\lvert\Delta m^2_{32}\rvert$	2.43e-3



Results

- 90% C.L. contours (-2ΔlnL = 4.61) produced from the MINOS appearance data for each neutrino mass hierarchy
- Marginalized over eight values of δ_{CP} with fixed set of oscillation parameters assumed

Parameter	Value
θ_{12}	0.600
θ_{13}	0.159
θ_{23}	0.785
Δm^2_{21}	7.59e-5
$\lvert\Delta m^2_{32}\rvert$	2.43e-3