Decoherence in Atmospheric sector

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Outline

- Introduction: Non standard effects on flavor conversion
- Decoherence Formalism
- Atmospheric Sector
- Summary

Effects on flavor oscillation

- Standard Oscillation Scenerio:
  The neutrinos produced/detected in weak interaction processes are flavor eigen states which are coherent superpositions of the mass eigenstates.
- Oscillation: The leading mechanism of flavor conversion
- Sub leading effects:
  - Neutrino decay
  - Wave packet decoherence
  - Environment induced decoherence
  - Non standard interactions
  - Neutrinos with varying mass

Coherent effects

- Some effective addition to the Hamiltonian
$$\bar{H} = H_s + H'$$
- Effects can be included in the probability level
- Example:
  - Non-standard interactions
  - Neutrinos with varying mass

Incoherent effects

- Damping effects
- Neutrino decoherence
- Neutrino decay

Effect on oscillation phases

- Coherent effects: May alter the oscillation phases
- Incoherent effects:
  - Cannot alter the oscillation phases
  - However contribute to the damping of overall probability/flux
- Incoherent effects may be probed primarily through their energy dependence

Categorizing Coherent+Incoherent effects

- Coherent effects: Probability conserving
- Incoherent effects:
  - Probability conserving ("decoherence like")
  - Probability non-conserving ("decay like ")
- **Open question: In case of combined effects: How do we distinguish them from each other?**

Quantum Decoherence

- Relevant energy scale for quantum gravity can be much lower than $\sim$ Plank energy
  [N. Arkani-Hamed et al. PLB 429 263 (1998);
  L. Randall et al. PRL 83 3370(1999), PRL 83 4690 (1999)]
- Even with a high energy scale of quantum gravity, relatively low energy physics may be sensitive to it
  [Ellis et al., Nucl. Phys. B 241 381 (1984)]
- Quantum decoherence: Quantum gravity induced quantum mechanical effect
- Wave packet motion / environment induced

Quantum Decoherence

- Simple models involving $\nu_\mu - \nu_\tau$ oscillations : was studied to put bounds on quantum decoherence effects.
- Early results: quantum decoherence effects slightly disfavored, but not completely rule out
- **Experimental sensitivity to decoherence: An Open Problem**
- Quantum gravity can change the energy dependence of the oscillation length
- Interesting for Oscillation + decoherence kind of models

Akhmedov et al. arXiv:1702.08338; Benatti et al. JHEP 02(2000)032; Liu et al. PRD 56(1997)6648; Klapodor-Kleingrothaus et al. EPJA 8(2000)577; Lisi et al. PRL 85(2000)1166; Fogli et al. PRD 67(2003)093006, Ashie et al[SK] PRL 93(2004)101801; Korolkova et al. [ANTARES] Nucl Phys Proc. Suppl 136(2004)69; [IceCube] ICRC 0484(2009)

Neutrino decoherence (system–environment type)

- Quantum systems that are 'open' to environmental influence can exhibit decoherence
- The environment might originate in couplings to new physics
- Consider a neutrino system to be coupled to an environment (may be a reservoir)
- System–environment type interactions: Even if initial state is a pure quantum mechanical state, the system–environment coupling would produce a mixed quantum mechanical state.
- Example: The Schroedinger equation can be substituted by a modified version of Lioville equation can be used to introduce decoherence effects

$$\dot{\rho} = -i[H_m, \rho] - D(\rho)$$

(Top) E = 1GeV, (Bottom) E = 200 GeV

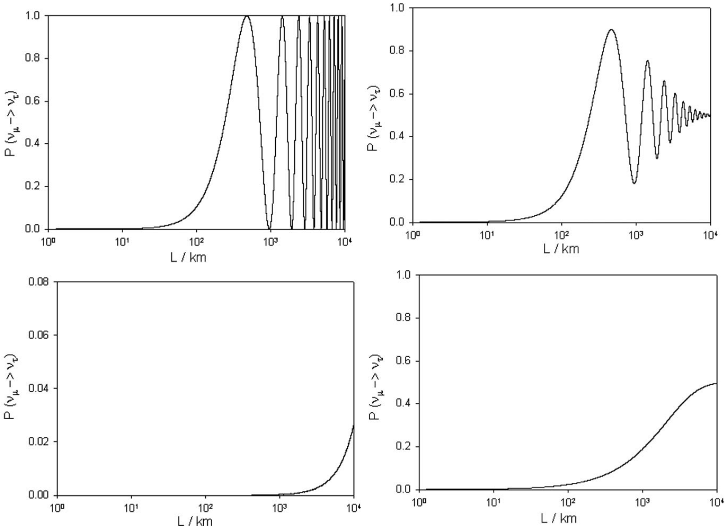

Figure: (Left)Standard Oscillation, (Right)E–independent decoherence

Some older results Morgan et al., AstroPart. Phy. 25(2006) 311-327

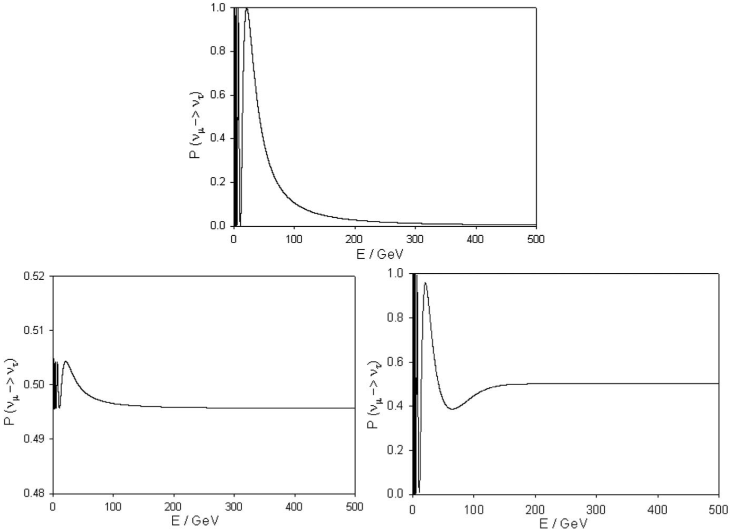

Figure: L = 10000 km. (Top)Standard Oscillation, (Bottom-left) E–independent decoherence, (Bottom-right) E–dependent decoherence

Quantum Decoherence

- Possible corrections can be added to oscillation experiments
- The energy and path length of atmospheric neutrinos: will be complementary to "long baseline" neutrino experiments
- Potential for bounding quantum decoherence and other damping signatures
- Gaussian uncertainties in the neutrino energy and path length, when averaged over, can incorporate similar effects on standard neutrino oscillation probability as caused by decoherence

T. Ohlsson, PLB 502(2001)159-166

ν decoherence in long baseline experiments

- Formalism of an environmentally induced decoherence, distinguished from neutrino wave packet decoherence
- Wave packet decoherence introduces exponential damping factors which multiply the oscillatory terms in the oscillation transition probabilities
- The damping due to wave packet decoherence depends strongly on the neutrino energy as well as on the baseline, and is not viable as an effect that can account for the apparent non-maximal neutrino mixing with a longer baseline.

Coelho et al. PRL 118,221801 (2017)

Nova: Results favoring non–maximal neutrino mixing

Coelho et al. PRL 118,221801 (2017)

- It is proposed that a small decoherence effect whose strength lies just below the current upper limit can account for the non-maximal mixing observation at NOvA while indicating why θ_{23} appears to be more nearly maximal at T2K
- The departure from maximal mixing can be accounted for by an energy-independent decoherence of strength $\Gamma = (2.3 \pm 1.1) \times 10^{-23}$

NOvA: possible decoherence effects

$$\mathcal{P}_{\mu\mu}^{(3\nu)} \approx 1 - \frac{1}{2}\sin^2\tilde{\theta}_{13}\sin^2 2\theta_{23}[1 - e^{-\Gamma_{21}L}\cos 2\tilde{\phi}_-]$$
$$- \frac{1}{2}\cos^2\tilde{\theta}_{13}\sin^2 2\theta_{23}[1 - e^{-\Gamma_{32}L}\cos 2\tilde{\phi}_+]$$
$$- \frac{1}{2}\sin^2 2\tilde{\theta}_{13}\sin^4\theta_{23}[1 - e^{-\Gamma_{31}L}\cos 2\tilde{\phi}_0], \qquad (3)$$

where

$$\tilde{\phi}_0 \equiv \phi\sqrt{(\cos 2\theta_{13} - \hat{A})^2 + \sin^2 2\theta_{13}}, \qquad (4)$$

$$\tilde{\phi}_\pm \equiv \frac{1}{2}[(1 + \hat{A})\phi \pm \tilde{\phi}_0], \qquad (5)$$

with the matter potential $\hat{A} = (2\sqrt{2}G_F N_e E_\nu)/\Delta m_{31}^2$ and with $\tan 2\tilde{\theta}_{13} = \sin 2\theta_{13}/(\cos 2\theta_{13} - \hat{A})$.

Coelho et al. PRL 118,221801 (2017)

NOvA: possible decoherence effects

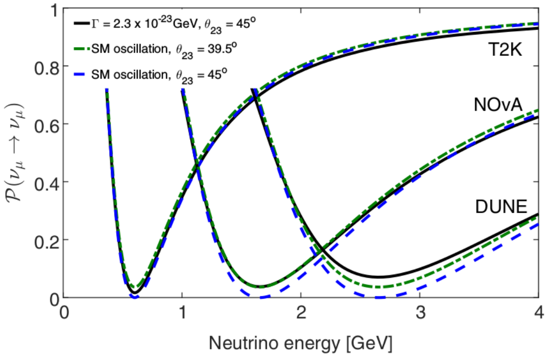

FIG. 1. Muon-neutrino survival versus E_ν at the T2K, NOvA, and DUNE baselines in the vicinity of their respective first minima. The probability distributions compare standard oscillations with maximal and nonmaximal θ_{23} mixing (the long-dashed and short-dashed curves), to oscillations with maximal mixing plus decoherence (the solid-line curve).

Coelho et al. PRL 118,221801 (2017)

NOvA: possible decoherence effects

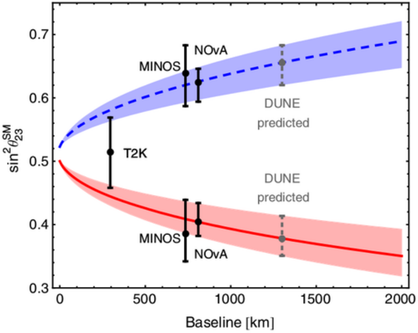

FIG. 2. Depiction of the trend toward a larger apparent deviation from maximal θ_{23} mixing with an increasing oscillation baseline, as predicted by the maximal mixing plus decoherence oscillation scenario. The predictions are double valued and asymmetric about $\sin^2\theta_{23} = 0.5$, reflecting the octant degeneracy inherent to a measurement of θ_{23} in the presence of matter effects. The curves displayed are for the normal mass hierarchy.

Coelho et al. PRL 118,221801 (2017)

Atmospheric neutrino sector & decoherence

- How does neutrino decoherence affect the matter effect?

  Coelho et al. arXiv:1708.05495

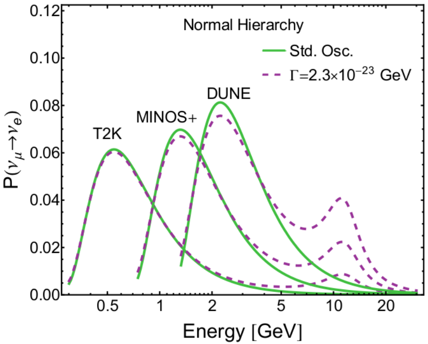

FIG. 1. Probability versus E_ν for $\nu_\mu \to \nu_e$ oscillations with environmental decoherence of strength Γ(dashed curve) for current long baseline experiments, assuming the normal mass hierarchy. In the case that the effective energy basis is the eigenbasis for the environmental "measurement", decoherence conspires with the terrestrial MSW matter effect to give a small ν_e appearance maximum at 12 GeV.

NOvA: possible decoherence effects

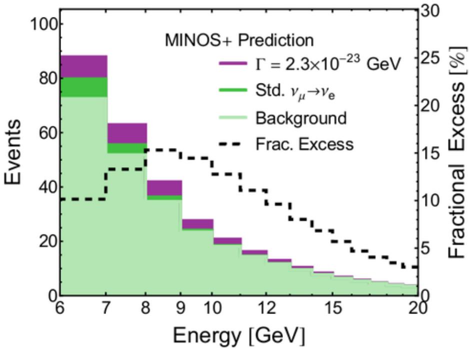

FIG. 2. Prediction for the excess of ν_e appearance events (uppermost histogram) that may occur in MINOS & MINOS+ data for the case of normal mass hierarchy. The enhanced ν_e rate arises from decoherence modification of the MSW resonance at $E_\nu = 12$ GeV. The estimation is based upon publicly presented fluxes and detection efficiencies and assumes investigation of the full $(10.56 + 10) \times 10^{20}$ POT exposures of MINOS and MINOS+ to the low-energy and medium-energy NuMI beams.

NOvA: Results favoring non–maximal neutrino mixing

Coelho et al. arXiv:1708.05495

If maximal θ_{23} mixing plus decoherence is operative but θ_{23} measurements continue to be expressed in terms of standard oscillations without decoherence, certain trends in neutrino results can be anticipated

- NOvA will continue to report non-maximal mixing.
- T2K results will gradually shift from maximal to non-maximal θ_{23} mixing, but with a deviation from maximal that is always less than that reported by NOvA.
- This apparent tension will hold regardless of whether ν_μ and $\bar{\nu}_\mu$ data samples are treated separately or together at each of the baselines

NOvA: Results favoring non maximal neutrino mixing

- At DUNE, a larger (apparent) deviation from maximal θ_{23} mixing will be observed than that reported by NOvA. Specifically, ν_μ disappearance in DUNE will appear to be governed by mixing at strength $\sin 2\theta_{23} = 0.38$ for the lower octant NH solution.

Sensitive tests of decoherence using atmospheric neutrinos may also be feasible; however, a careful accounting of matter effects for ν_μ as well as $\bar{\nu}_\mu$ fluxes with a consideration of mass hierarchy is required

Open problems

- More probe of a decoherence formalism in the atmospheric sector, with detailed input of the 3-flavor mixing parameters
- Decoherence: Wave packet Vs Environment induced
- Impact on different MH, θ_{23} octant etc.
- Oscillation + decoherence scenario: Impact on survival/oscillation probability, baseline, matter effect
- Test with experimental data. Should the formalism be consistent for different source, production mechanisms?
- Oscillation+ decay + decoherence + sterile + ...
- A scan over the 3σ range of the mixing parameters to get possible range of the decoherence parameters

Thank you for the kind attention!