Exotic Oscillations Searches at HK: Sterile Neutrinos and Lorentz Violation

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HK Collaboration Meeting

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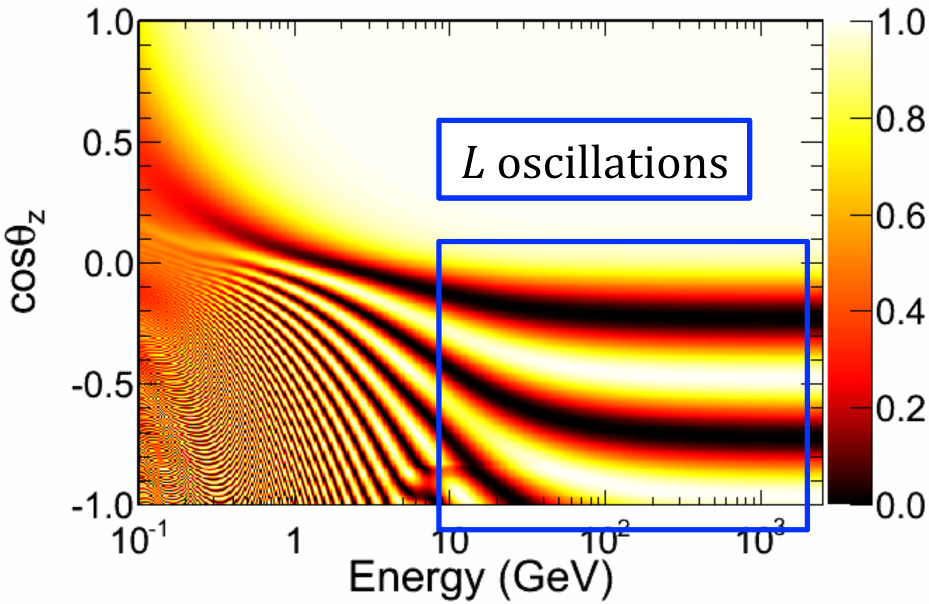
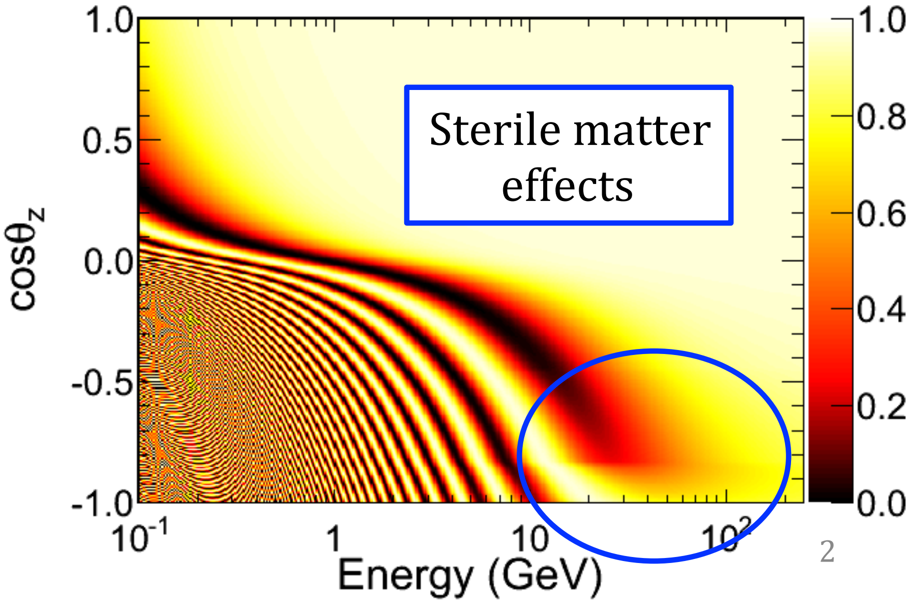
Lorentz Violation and Sterile Neutrinos

- Searches for exotic oscillations mixed with standard 3-flavor oscillations
- Lorentz violation:
  - *L* and *LE* oscillations
- Sterile neutrinos:
  - Fast oscillations at short distances
  - Sterile matter effect at long distances

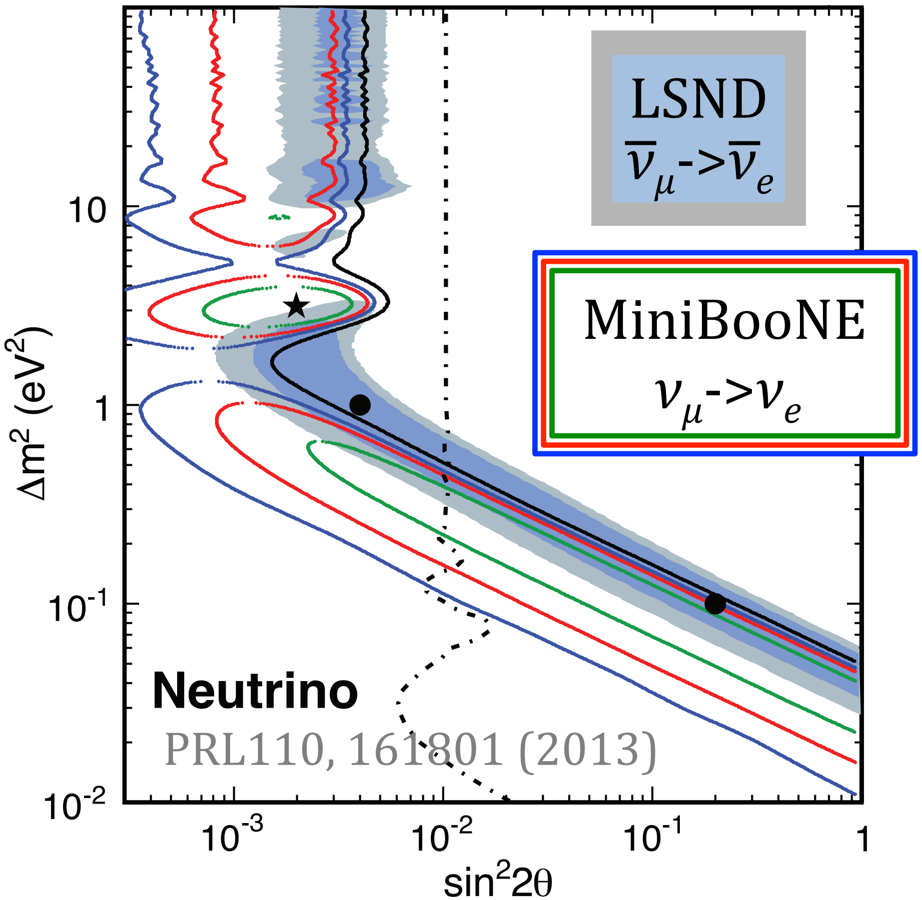


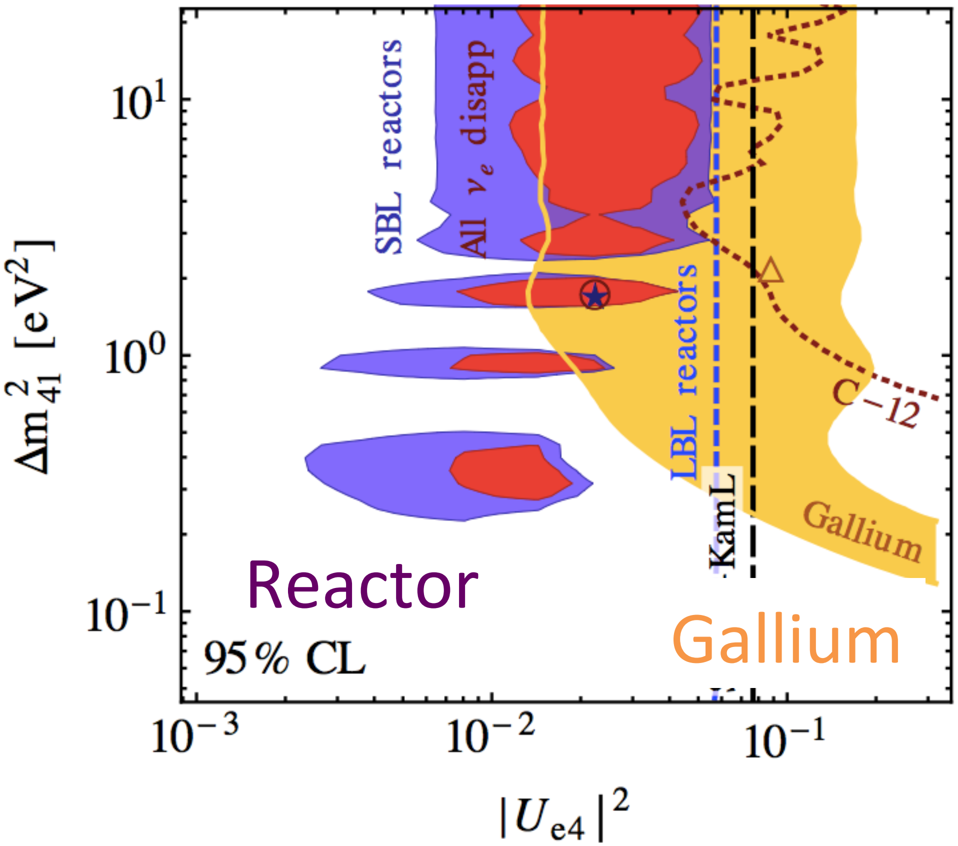


Sensitivity Studies

- Presenting sensitivity studies to non-standard oscillations based on analyses in SK.
- Scaling SK-II MC sensitivities to:
  - 10 years of livetime
  - 560/22.6 for FC/PC (scale by mass)
  - 14.4 for Up-μ (scale by area)
- Constrain 3-flavor oscillation parameters based on external measurements:
  - Errors included as uncertainties
  - Sources:
    - T2K 2014 PRL ν_μ disappearance for θ_{23}, $\Delta m^2{}_{23}$
    - SK Solar for θ_{12}, $\Delta m^2{}_{12}$
    - PDG weighted average for θ_{13}

Sterile Neutrinos





ν_e Appearance

$$\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

ν_e Disappearance

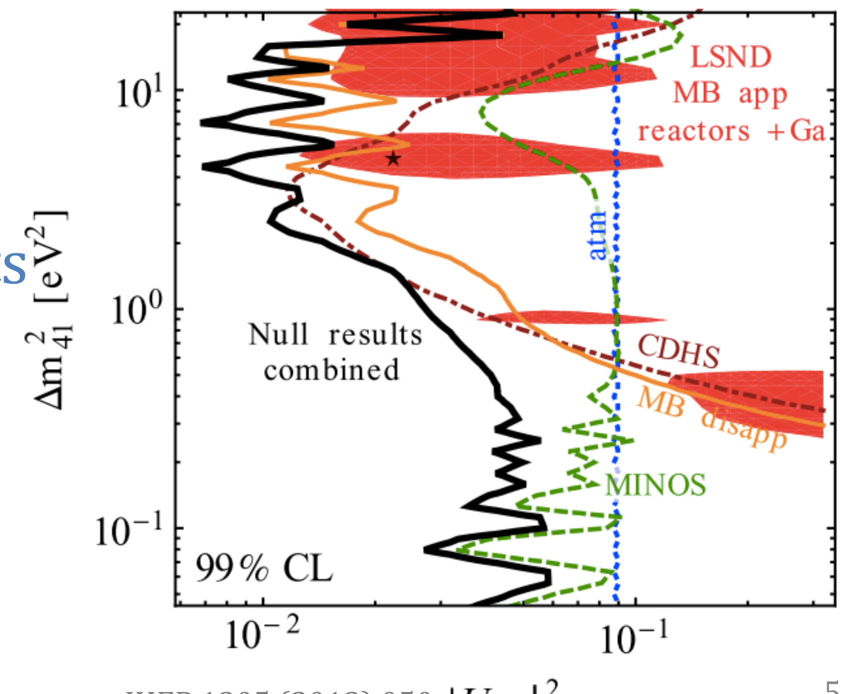
$$\sin^2 2\theta_{ee} = 4|U_{e4}|^2(1 - |U_{e4}|^2)$$

Not so simple…

- With only 1 sterile neutrino, should see three correlated signatures:
  - ν_e appearance
  - ν_e disappearance
  - ν_μ disappearance

$$\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$$
$$\sin^2 2\theta_{ee} = 4|U_{e4}|^2(1-|U_{e4}|^2)$$
$$\sin^2 2\theta_{\mu\mu} = 4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)$$

- No evidence yet of ν_μ disappearance
  - Creates tension in global fits
- Models with additional neutrinos tried
  - No consensus yet



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Super-K Sterile Model

- A fully generic sterile model is difficult computationally
  - Cannot calculate both active (ν_e) and sterile (NC) matter effects together
- So, we need to perform 2 different fits:

No-ν_e Fit	Sterile Vacuum Fit
– Fit for $\lvert U_{\tau 4}\rvert^2 + \lvert U_{\mu 4}\rvert^2$ – NC matter effects only – Required for $\lvert U_{\tau 4}\rvert^2$ – Over-constrains $\lvert U_{\mu 4}\rvert^2$	– Fit for $\lvert U_{\mu 4}\rvert^2$ only – ν_e matter effects only – Most accurate $\lvert U_{\mu 4}\rvert^2$ limit – No $\lvert U_{\tau 4}\rvert^2$ limit

No-ν_e Fit

- The ν_μ survival probability (3+1):

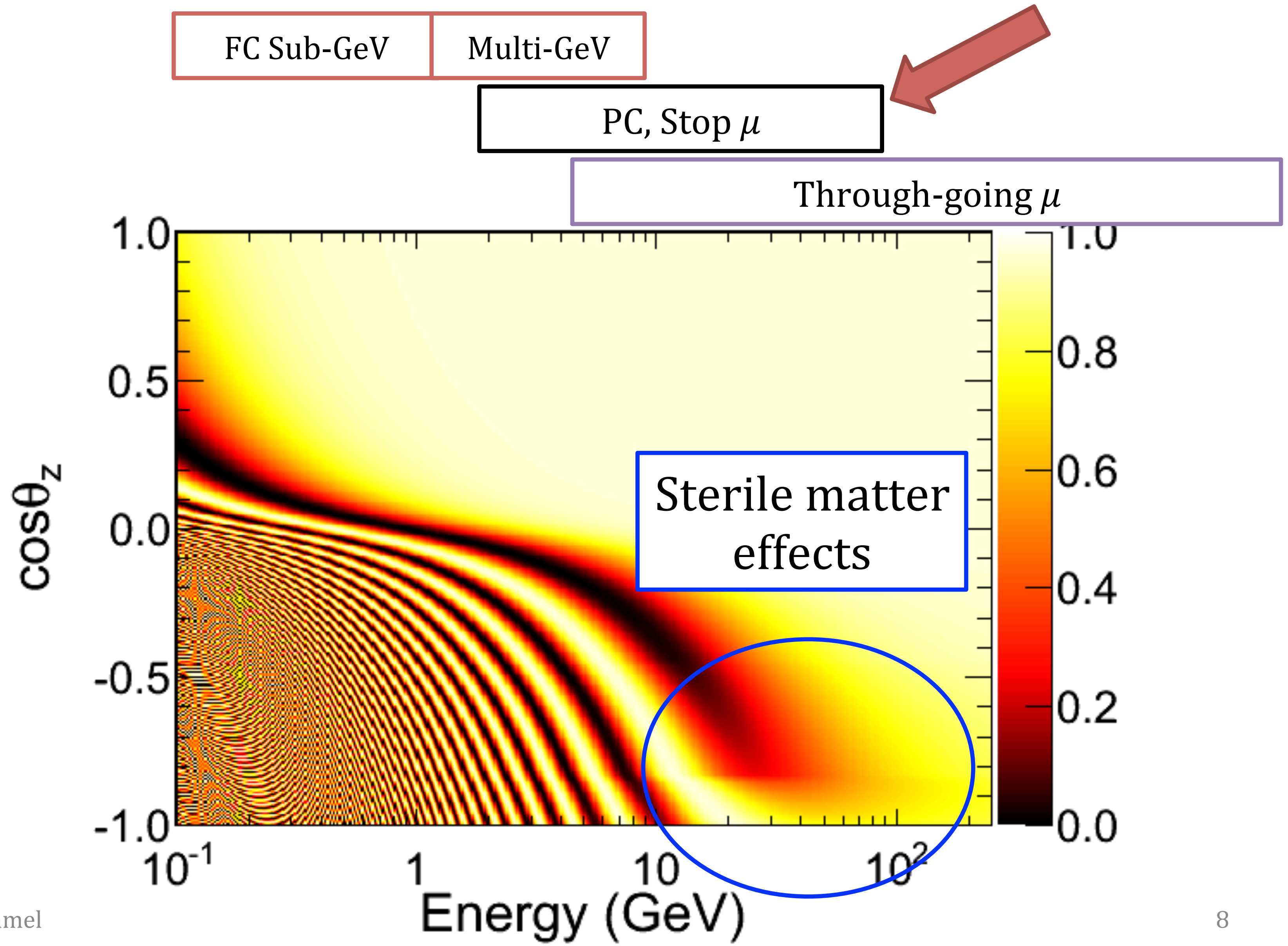
$$P_{\mu\mu} = \left(1 - |U_{\mu 4}|^2\right)^2 P_{\mu\mu}^{(2)} + |U_{\mu 4}|^4$$

$$H^{(2)} = H_{sm}^{(2)} + H_s^{(2)} :$$
$$= \frac{\Delta m_{31}^2}{4E} \begin{pmatrix} -\cos 2\theta_{23} & \sin 2\theta_{23} \\ \sin 2\theta_{23} & \cos 2\theta_{23} \end{pmatrix} \pm \frac{G_F N_n}{\sqrt{2}} \begin{pmatrix} |\tilde{U}_{s2}|^2 & \tilde{U}_{s2}^* \tilde{U}_{s3} \\ \tilde{U}_{s2} \tilde{U}_{s3}^* & |\tilde{U}_{s3}|^2 \end{pmatrix}$$

- 2-level system is the benefit of decoupling ν_e's from oscillations

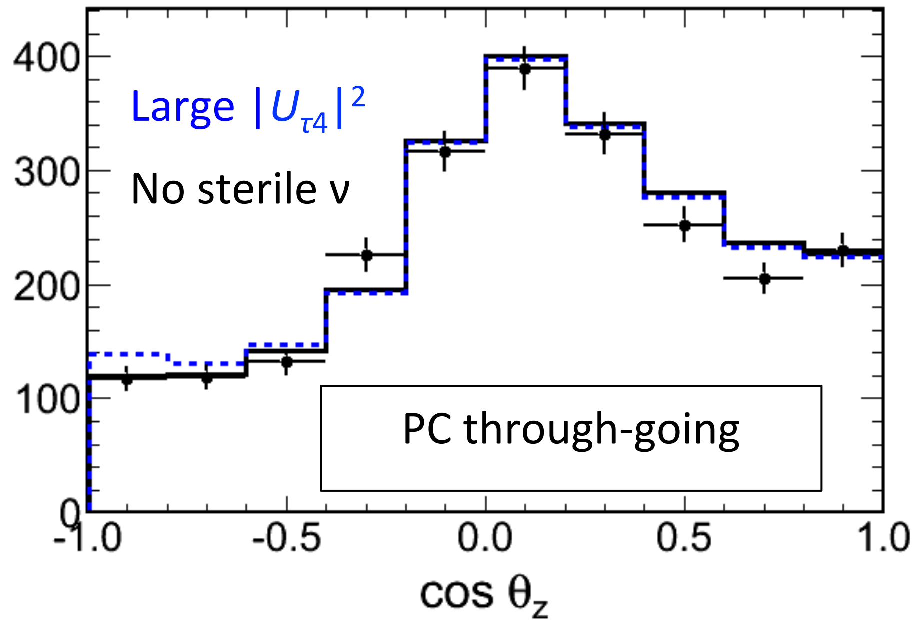
- $\tilde{U}_{si}$ can be written in terms of $|U_{\tau 4}|^2$ and $|U_{\mu 4}|^2$ in a 3+1 framework

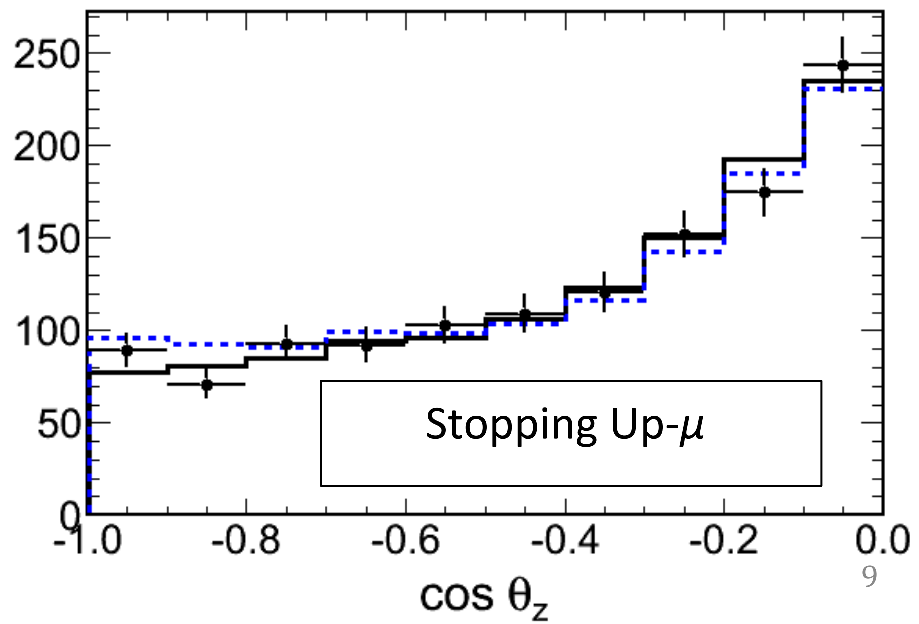
No-ν_e Oscillogram



Example Zenith Distributions

- Most sensitive samples
  - Energies ~10 GeV
- Less disappearance at long path-lengths
  - Up-going events
- Systematic errors fit to both hypotheses
  - Large differences in oscillation probability reduced by systematic errors





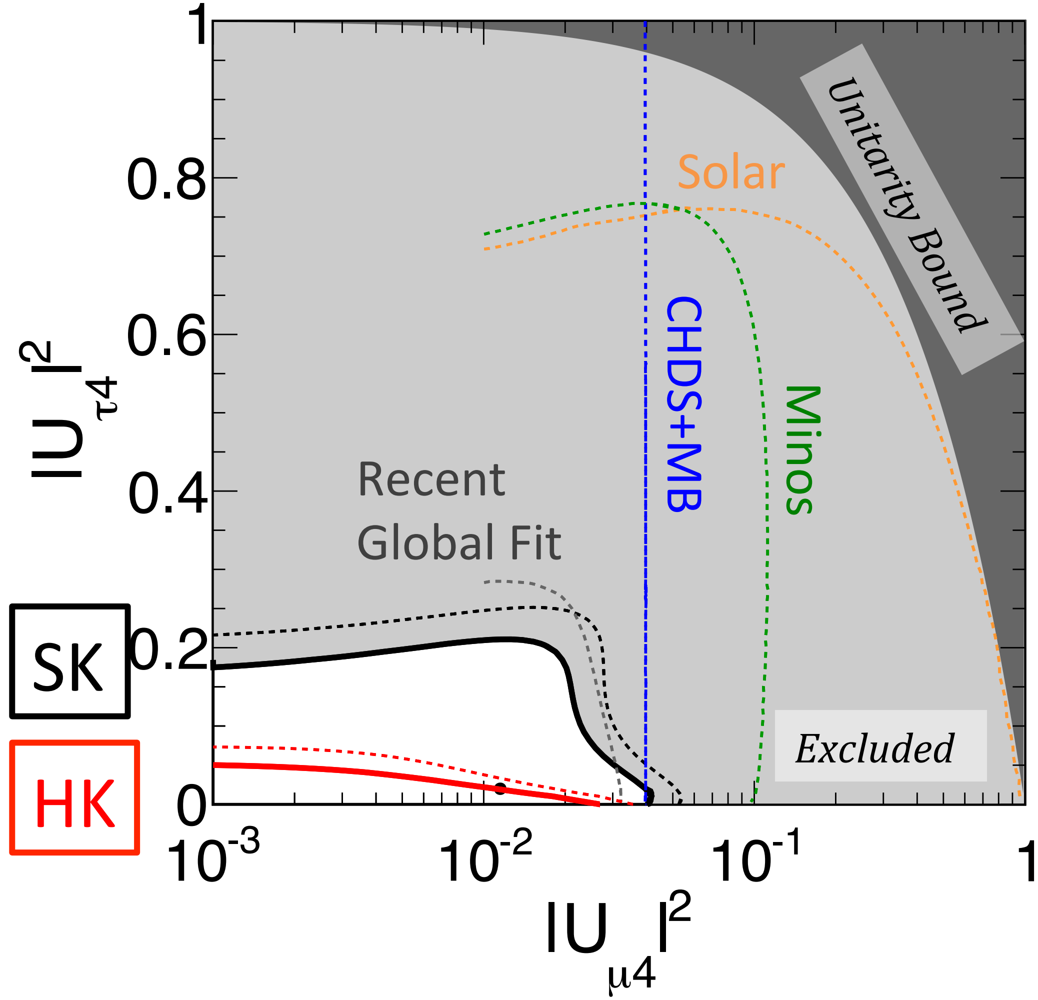
No-ν_e Fit Results

99% $|U_{\tau 4}|^2$ Sensitivity

SK: 0.164

HK: 0.066

Significant improvement with the increase in PC statistics.



All comparisons from: JHEP 1305 (2013) 050

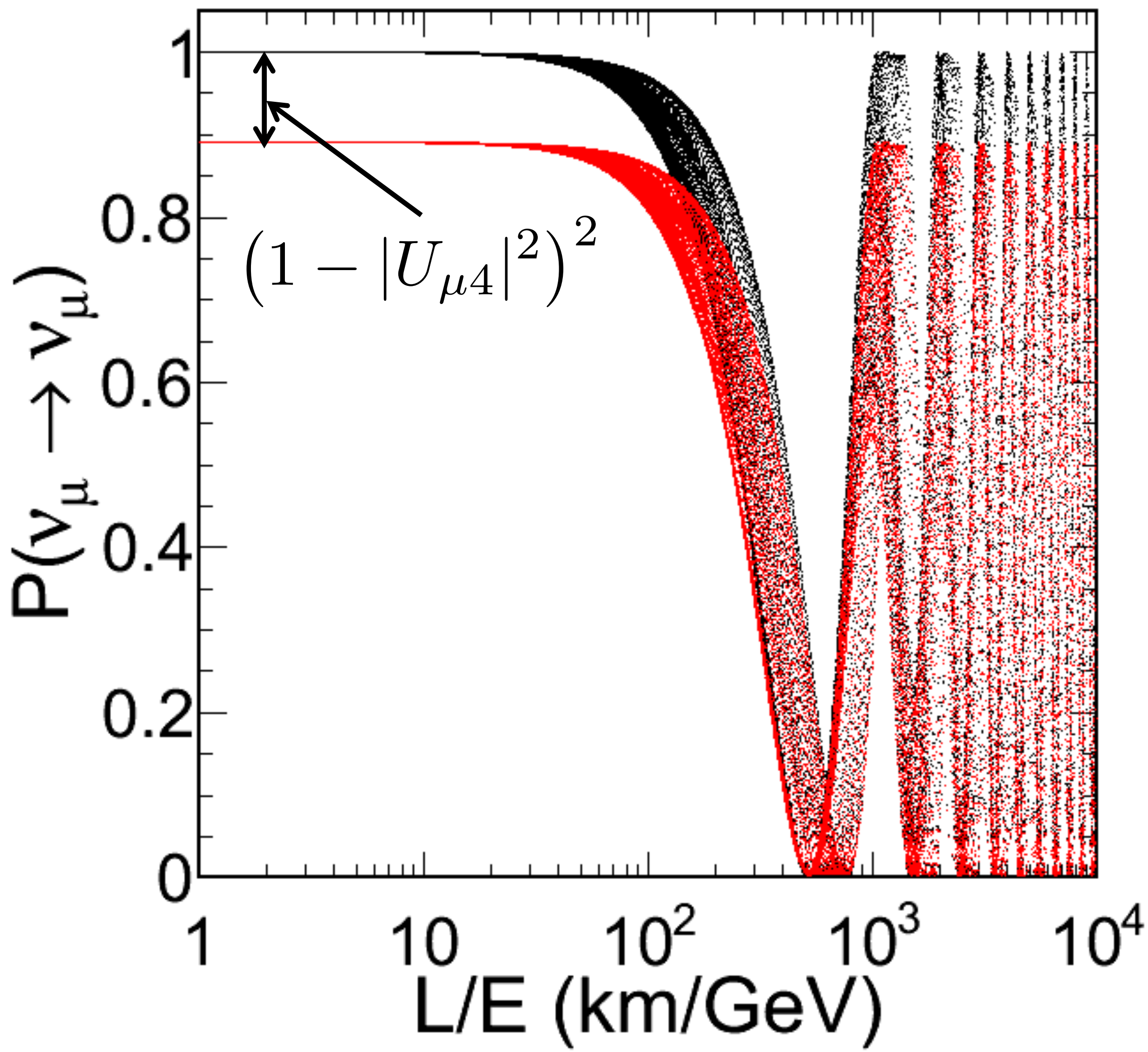
Sterile Vacuum Fit

- The ν_μ survival probability in 3+1:

$$P_{\mu\mu} = \left(1 - |U_{\mu 4}|^2\right)^2 P_{\mu\mu}^{(3)} + |U_{\mu 4}|^4$$

- Here, $P^{(3)}$ is just the standard 3-flavor oscillation probability
  - Includes ν_e matter effects – get e-like sample normalization right
  - Does not include $|U_{\tau 4}|^2$

Sterile Vacuum Oscillations vs. *L/E*



Sterile Vacuum Fit Results

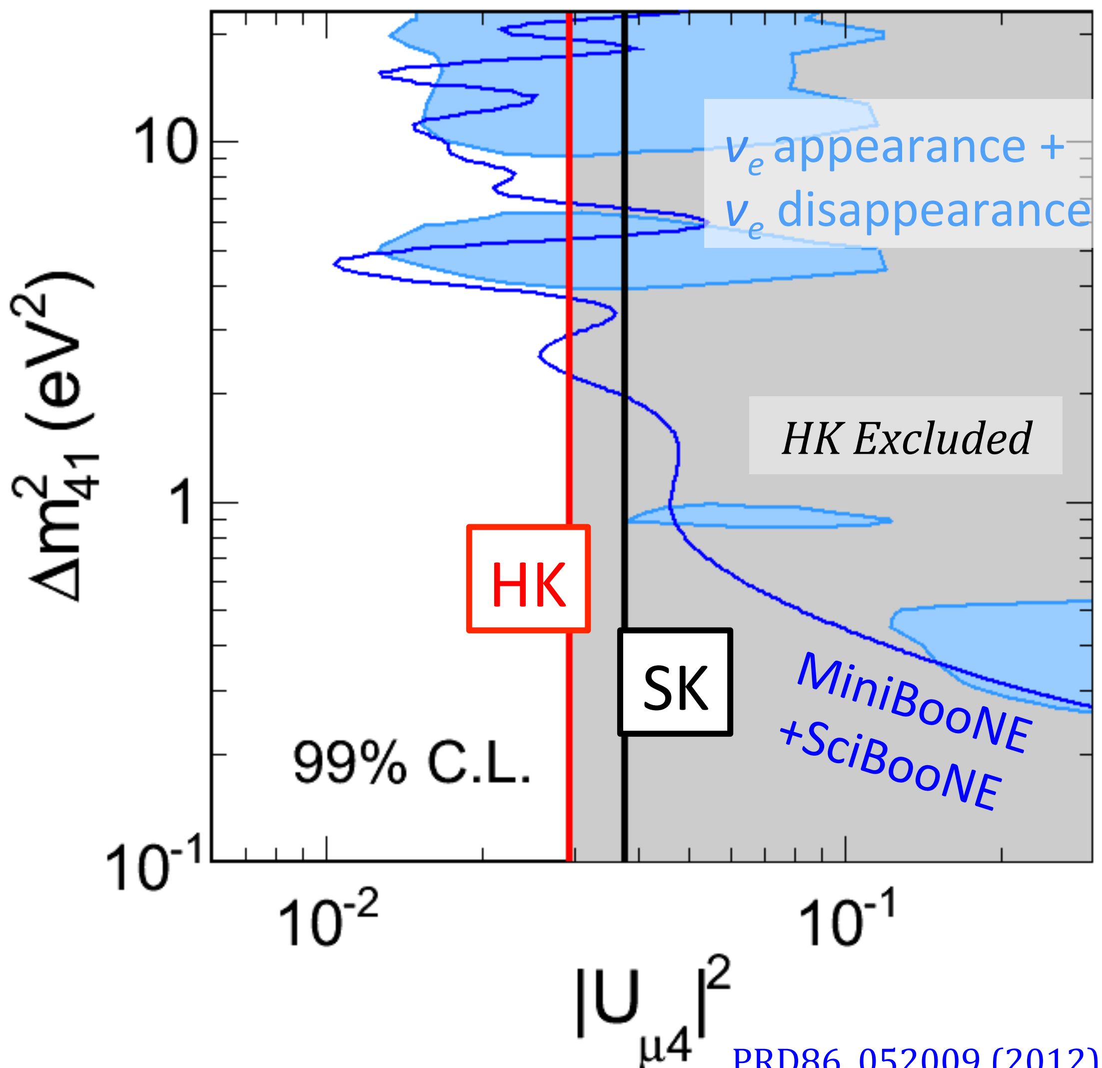
99% $|U_{\mu 4}|^2$ Sensitivity

SK: 0.038

HK: 0.029

Improvement with HK is marginal.

Analysis is dominated by systematic errors on flu and cross-section normalization.



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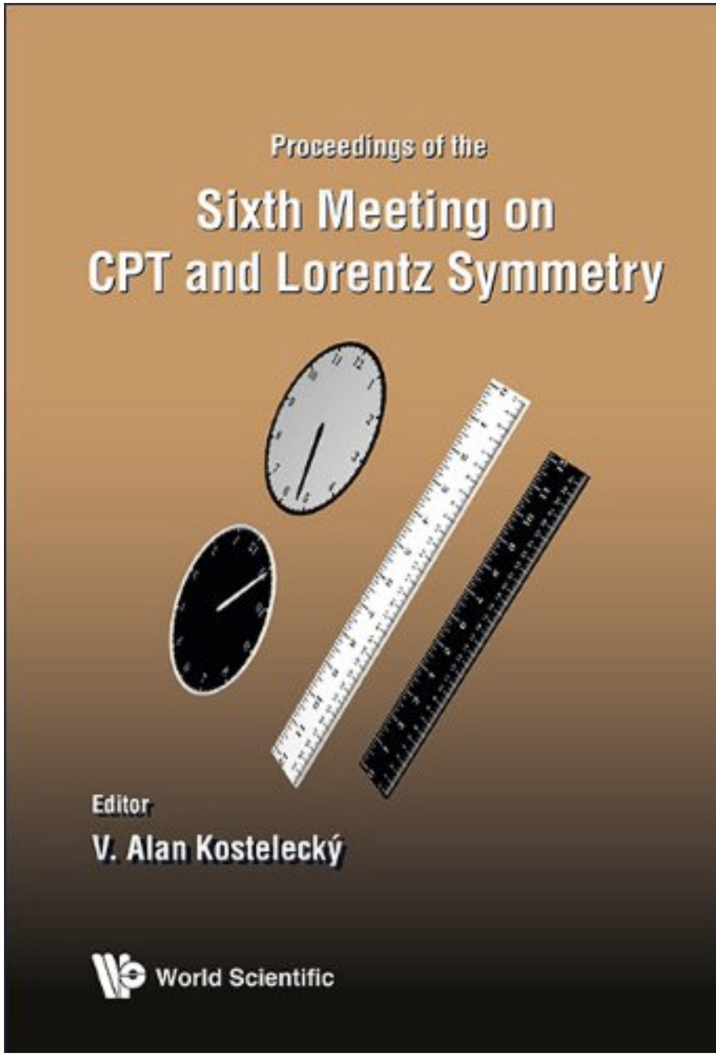
Lorentz Invariance

- A fundamental symmetry in QFT and general relativity, but small violations predicted in some models
  - Discrete spacetime structure
  - Spacetime foam
- The Standard Model Extension (SME)
  - A QFT with all the properties of the standard model which adds parameters to allow all possible LV terms
- Tested in a wide variety of contexts, including other neutrino experiments
  - MINOS, Double Chooz, LSND, MiniBooNE…



Standard Model Extension

	Coefficient	Unit	d	CPT	Oscillation Effect
SK	**Isotropic**				
	$a^{T}_{\alpha\beta}$	GeV	3	odd	$\propto L$
	$c^{TT}_{\alpha\beta}$	-	4	even	$\propto LE$
Prev. Exp.	**Directional**				
	$a^{X}_{\alpha\beta}, a^{Y}_{\alpha\beta}, a^{Z}_{\alpha\beta}$	GeV	3	odd	sidereal variation
	$c^{XX}_{\alpha\beta}, c^{YZ}_{\alpha\beta}, \ldots$	-	4	even	sidereal variation

- Focusing on the terms which just affect $\nu \to \nu$ oscillation probabilities
  - Other terms generate $\nu \to$ anti-ν transitions

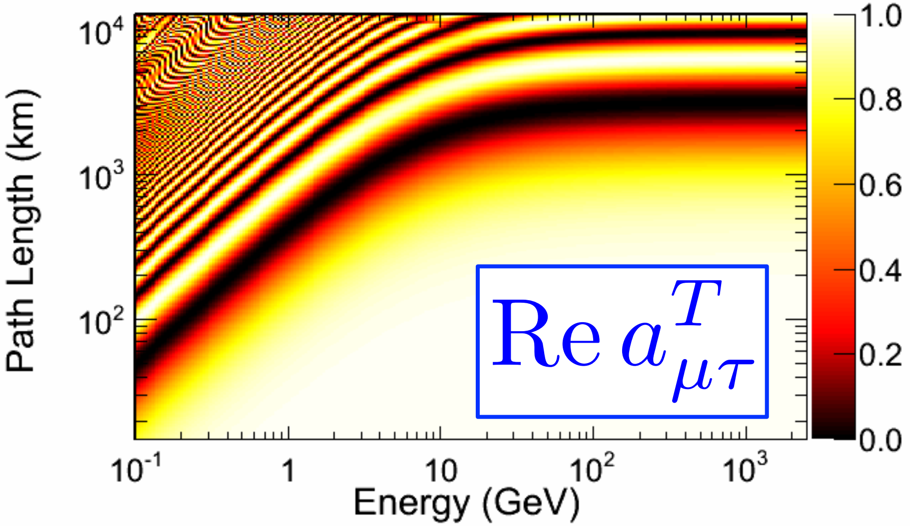
Neutrino Oscillations with SME

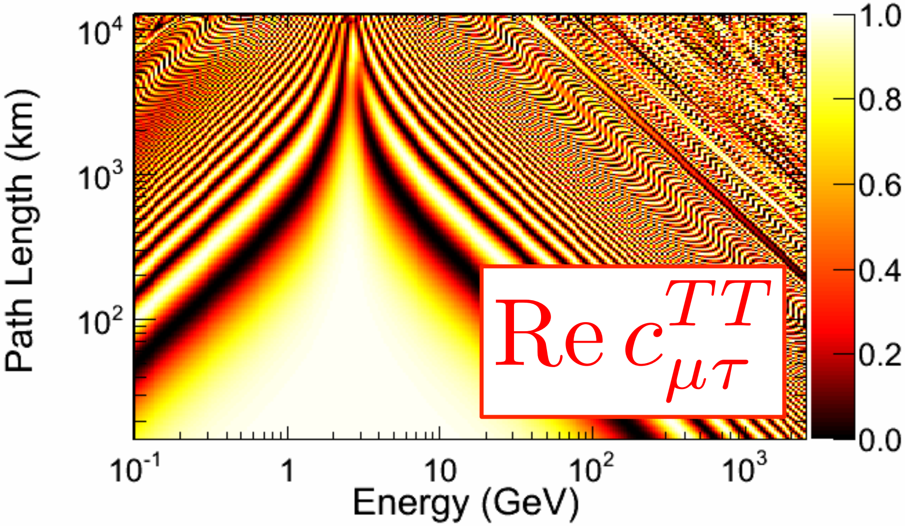
$$H = U\Delta U^\dagger + V_e + H_{LV}$$

$$H_{LV} = \begin{pmatrix} 0 & a^T_{e\mu} & a^T_{e\tau} \\ \left(a^T_{e\mu}\right)^* & 0 & a^T_{\mu\tau} \\ \left(a^T_{e\tau}\right)^* & \left(a^T_{\mu\tau}\right)^* & 0 \end{pmatrix} - \frac{4E}{3}\begin{pmatrix} 0 & c^{TT}_{e\mu} & c^{TT}_{e\tau} \\ \left(c^{TT}_{e\mu}\right)^* & 0 & c^{TT}_{\mu\tau} \\ \left(c^{TT}_{e\tau}\right)^* & \left(c^{TT}_{\mu\tau}\right)^* & 0 \end{pmatrix}$$

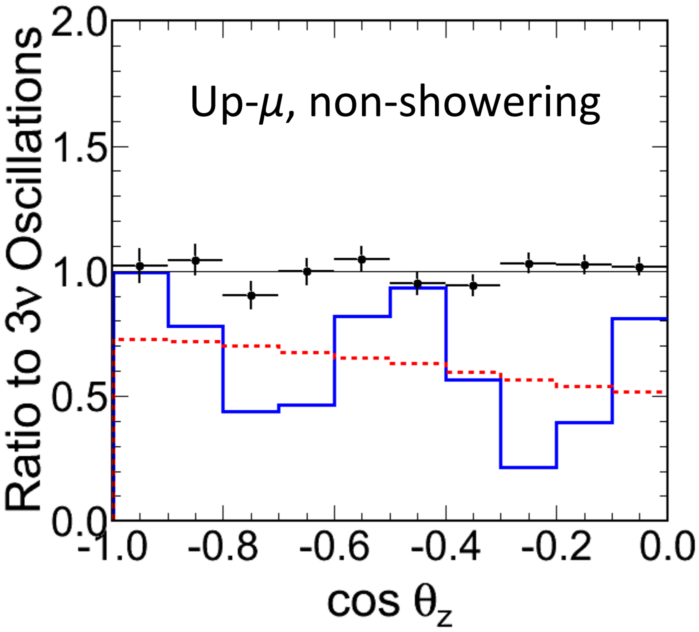
- Previous experiments used 1 of 2 approximations:
  - The short-baseline approximation where there are only *LV* oscillations
  - The perturbative approximation where H_{LV} is assumed to be small.
- Neither is appropriate for SK
  - 30% of our events fail the perturbative conditions
- We use, for the first time, the full diagonalization of the Hamiltonian to calculate oscillation probabilities.

Lorentz Violation





- a^T introduces L oscillations at high energy
- c^{TT} introduces LE oscillations at high energy



LV Sensitivity

	$e\mu$	$e\tau$	$\mu\tau$		$e\mu$	$e\tau$	$\mu\tau$
$\Re(a^T)$ (GeV)	4×10^{-20} MiniBooNE	8×10^{-20} Double Chooz	-	$\Re(c^{TT})$	1×10^{-19} MiniBooNE	1×10^{-17} Double Chooz	-
SK:	2×10^{-23}	4×10^{-23}	6×10^{-24}		2×10^{-26}	1×10^{-24}	5×10^{-27}
HK:	7×10^{-24}	2×10^{-23}	2×10^{-24}		6×10^{-27}	7×10^{-25}	2×10^{-27}

- Limits improve by a factor of 1.8-3.6 relative to SK sensitivity
  - sqrt(14.4×10 years / 13 years) = 3.3
- Improvements are as expected: incremental on the scale of these searches.

Conclusions

- Sensitivity studies to non-standard oscillations performed by increasing SK-II lifetime for existing SK studies.
- Sterile neutrino search:
  - Improvement in $|U_{\tau 4}|^2$ limit thanks to increased PC statistics
  - Marginal improvement in $|U_{\mu 4}|^2$ limit since that is systematically limited
- Lorentz violation search:
  - Improvements of a factor of 2-3
  - Consistent with increase in Up-μ statistics.

Backups

No-ν_e Fit in 3+N

- The 2-level system in 3+N

$$H^{(2)} = H_{\rm SM} \pm \underbrace{\frac{G_F N_n}{\sqrt{2}} \sum_\alpha \begin{pmatrix} |\tilde{U}_{\alpha 2}|^2 & \tilde{U}^*_{\alpha 2}\tilde{U}_{\alpha 3} \\ \tilde{U}_{\alpha 2}\tilde{U}^*_{\alpha 3} & |\tilde{U}_{\alpha 2}|^2 \end{pmatrix}}_{H_s(A_s,\,\theta_s)}$$

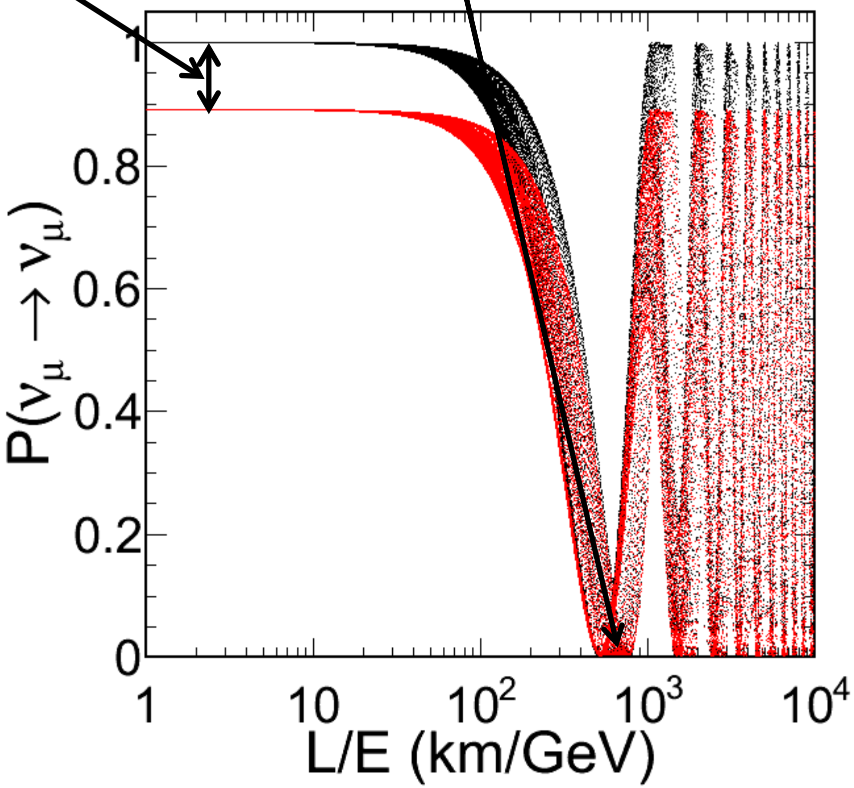
- Extend to multiple sterile neutrinos with a sum over sterile species α
- Because it is a 2-level system, any number of sterile parameters reduce to 3: A_s, θ_s, $|U_{\mu 4}|^2$
- We also make the results of this fit available in these parameters.

Sterile Vacuum Fit in 3+N

- The ν_μ survival probability in 3+N:

$$P_{\mu\mu} = \left(1 - d_\mu^2\right)^2 P_{\mu\mu}^{(3)} + \sum_\alpha |U_{\alpha 4}|^4$$

$$d_\mu = \sum_\alpha |U_{\alpha 4}|^2$$

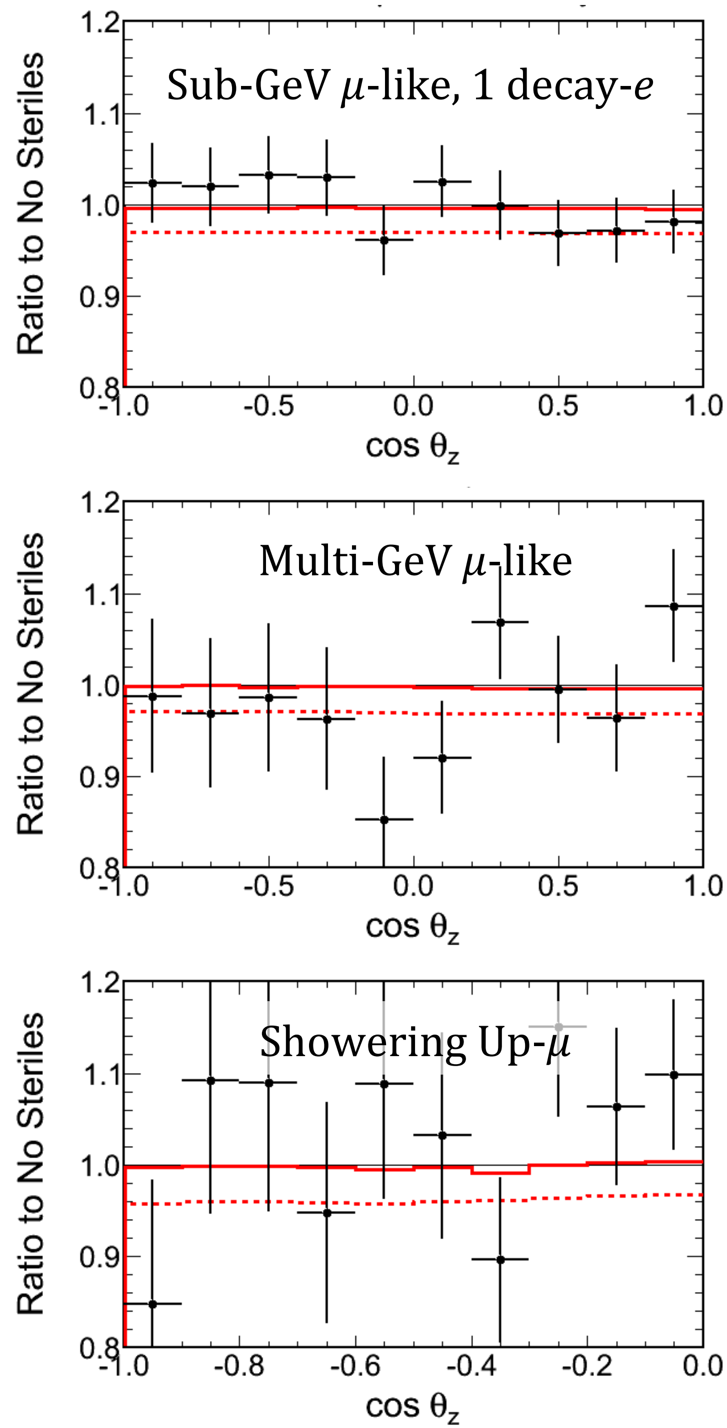


- Very similar to the 3+1 formula with $|U_{\mu 4}|^2 \rightarrow d_\mu$
- Correspondence is not exact in constant term but that term is second-order and much harder to observe

Sterile Vacuum Results

- Best fit: $|U_{\mu 4}|^2 = 0.016$
  - Shown as solid line at right
  - Dashed line shows fit without minimizing systematics
- All of the χ^2 improvement at best fit is in systematics.
  - Fit is systematically limited

Systematic	No Steriles	Best Fit
ν_μ/ν_e flux, $E < 1$ GeV	-0.52σ	-0.07σ
ν_μ/ν_e flux, E 1-10 GeV	-0.50σ	-0.11σ
CCQE ν_μ/ν_e	0.38σ	-0.01σ



Sterile Vacuum Fit Results

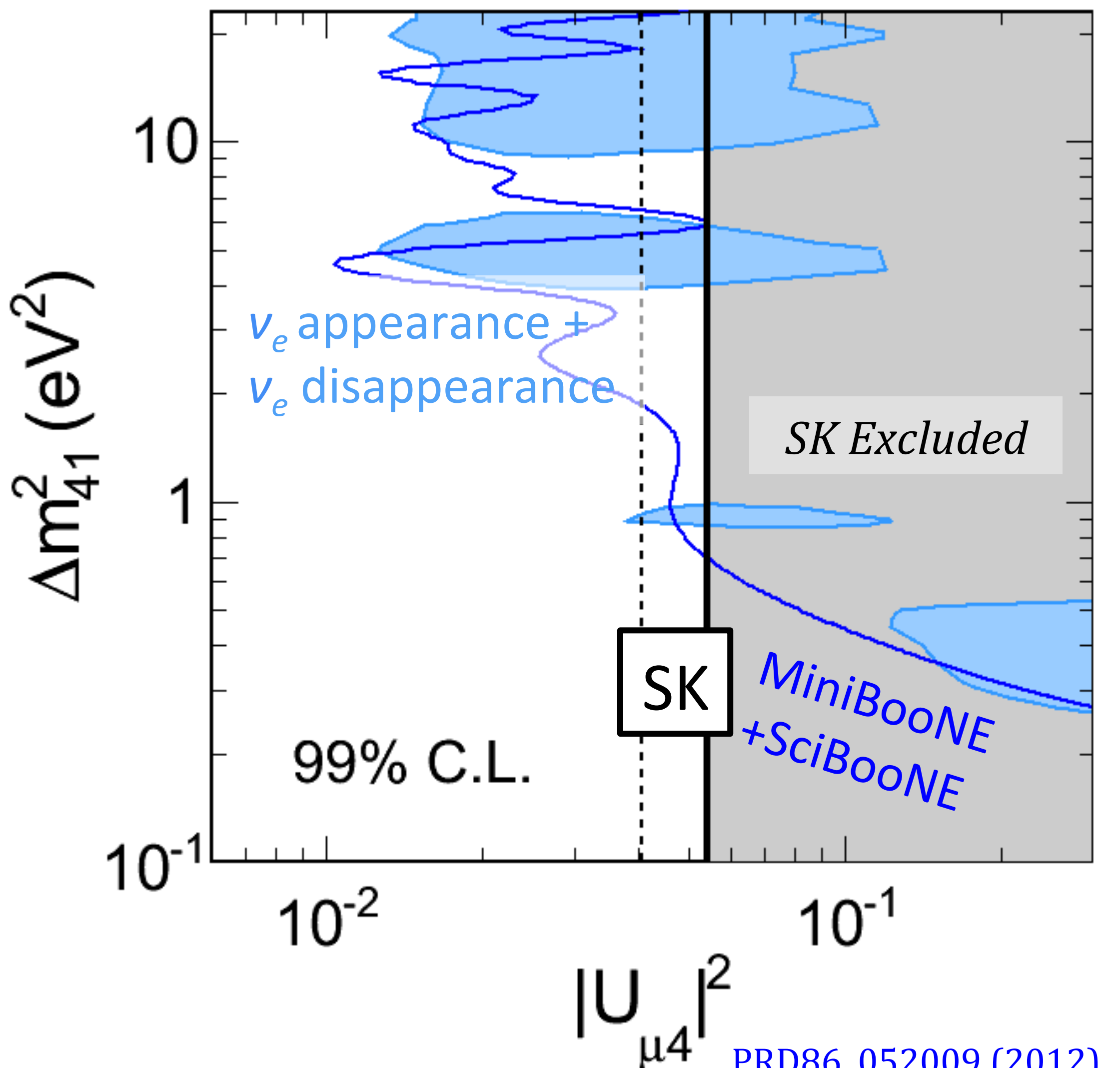
$|U_{\mu 4}|^2 < 0.041$ at 90% C.L.

$|U_{\mu 4}|^2 < 0.054$ at 99% C.L.

Sensitivity: 0.024 at 90%

As with similar experiments, no strong sterile-driven ν_μ disappearance

- $\Delta\chi^2$ of 1.1 between the best fit and no sterile neutrinos.



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Extending to 3+*N* Models: Hydrogen-Earth

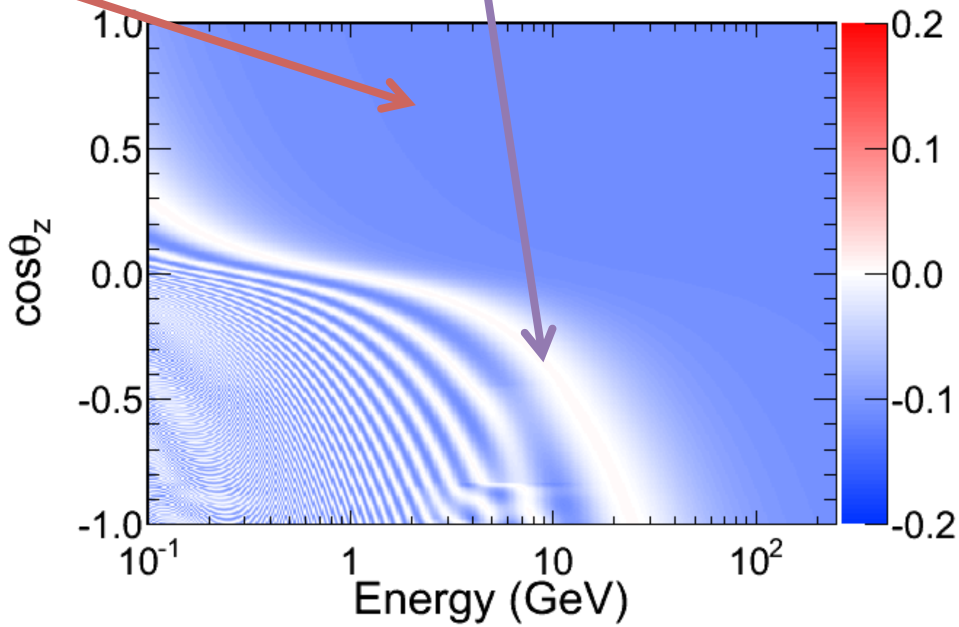
$$P_{\mu\mu} = (1-d_\mu)^2 P^{(3)}_{\mu\mu} + \sum_{i\geq 4} |U_{\mu i}|^4$$

- Substitute sum for single value

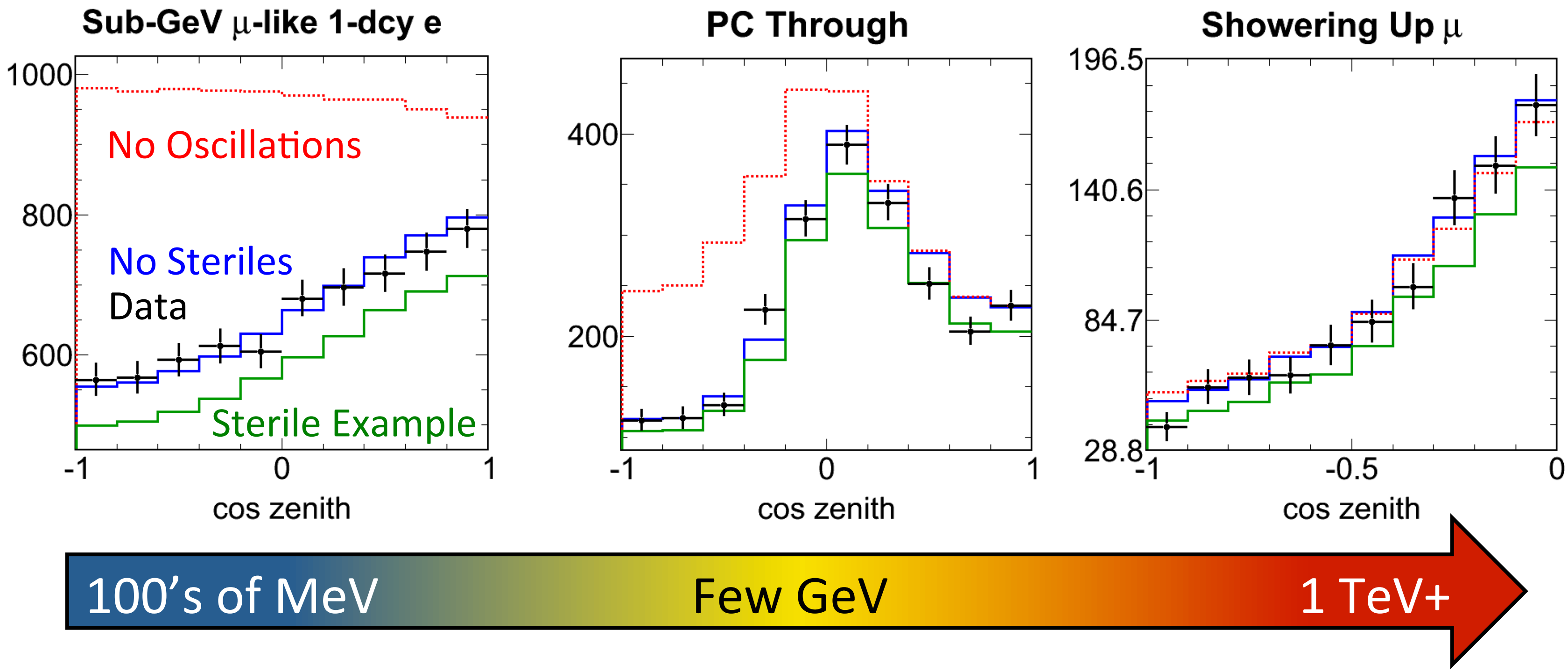
  $$|U_{\mu 4}|^2 \rightarrow d_\mu = \sum_{i\geq 4} |U_{\mu i}|^2$$

- Exact in first term, approximate in the second

- SK is *much* more sensitive to the first term than the second

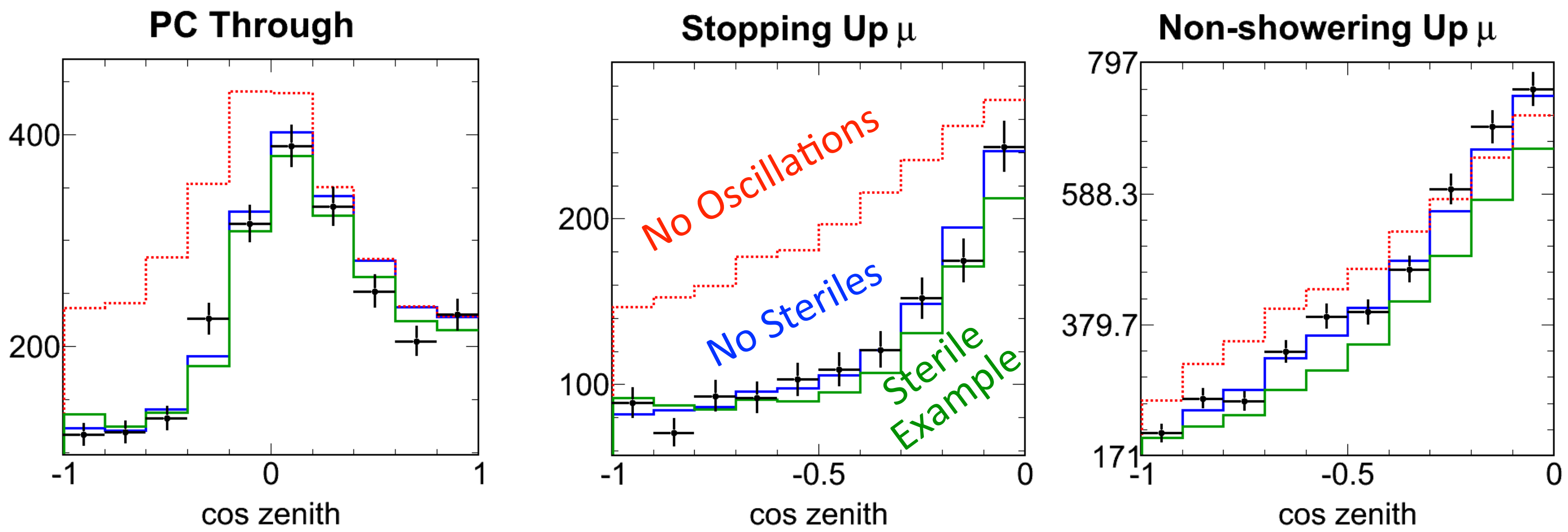


Fit for $|U_{\mu 4}|^2$



- Signature is extra disappearance in all μ samples
  - Correlated change at all energies, all $\cos\theta_z$
  - μ/e flux uncertainty an important systematic
- Bug was in this fit – NC events were not oscillating
  - Sensitivity improved by a few percent

Fit for $|U_{\tau 4}|^2$ (with $|U_{\mu 4}|^2$)



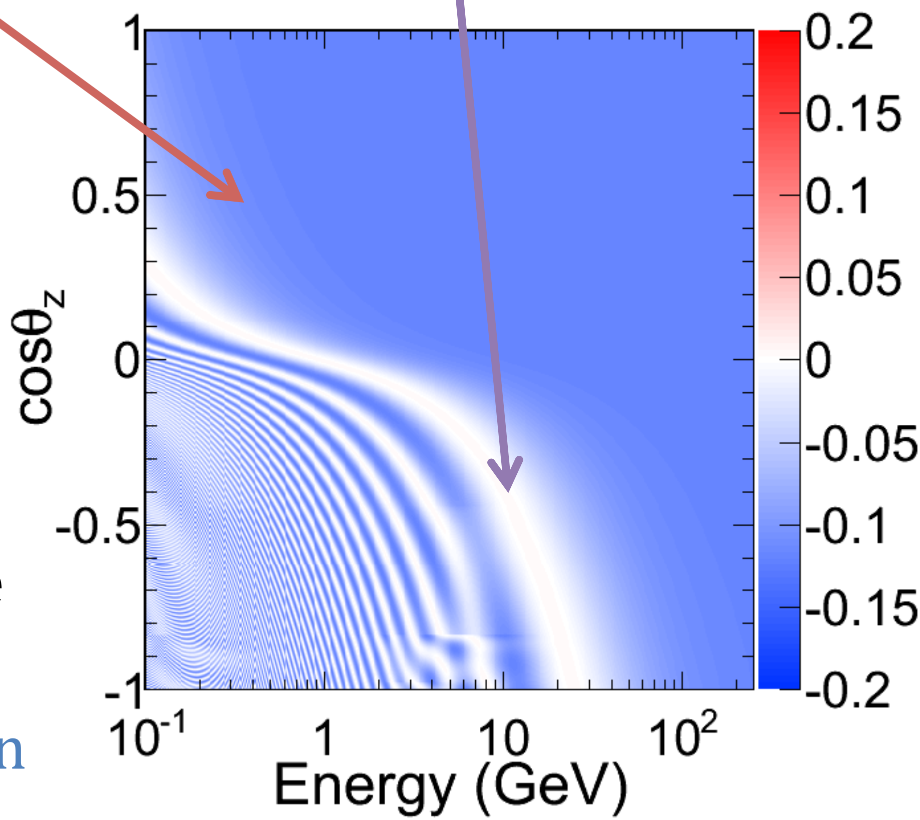
5-100 GeV

- NC Matter effects create shape distortion in PC/Up-μ zenith distribution
  - Less disappearance in most upward bins, still have extra disappearance in downward bins

3+N ≈ 3+1 for Super K

$$P_{\mu\mu} = \left(1 - |U_{\mu 4}|^2\right)^2 P^0_{\mu\mu} + \sum_{i\geq 4} |U_{\mu i}|^4$$

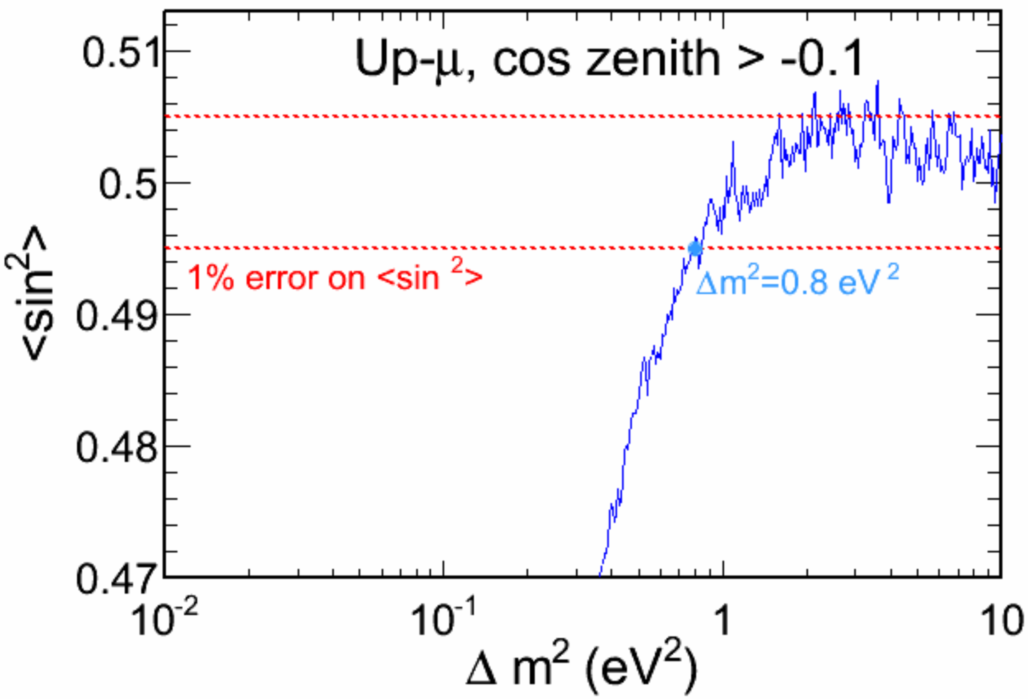
- The first sterile term:
  - Controls extra disappearance
  - Is the same for any Nsterile
- The second sterile term:
  - Fills in the minima
  - Varies for Nsterile
- Our experiment is *much* more sensitive to first term
  - Beam experiments, focusing on the first oscillation dip, *are* sensitive to the second term.



When is $\Delta m^2{}_{41}$ no longer "large"?

- When do the oscillations no longer appear fast?
  - This will be the worst at short L's and large E's, so lets focus on Up-μ with cos θ_z > -0.1
  - Loop through all these events and calculate the mean of $\sin^2(\Delta m^2 L/4E)$ for various Δm^2

- Doing this, the approximation is valid down to $\sim$0.8 eV^2



When is Δm^2_{41} no longer "large"?

- However, the limit on $|U_{\mu 4}|^2$ is driven by the low $|U_{\tau 4}|^2$ region.
  - In this region, the dominant samples are Sub-GeV muons
  - Almost no power comes from Up–μ
- For these samples, the "large" assumption is ~always valid so $|U_{\mu 4}|^2$ limit really is a vertical line in Δm^2 to a good approximation