Constraining Sterile Neutrinos at IceCube

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Hints for $\bar{\nu}$ anomaly

- LSND anomaly **A. Aguilar et al. (2001)**

- MiniBooNE consistent with LSND $\bar{\nu}$ data

  A. Aguilar-Arevalo et al. (2001)

- Reactor experiments:
  More $\bar{\nu}_e$ disappearance from flux re-evaluation?

  T. Mueller, et. al. (2011)
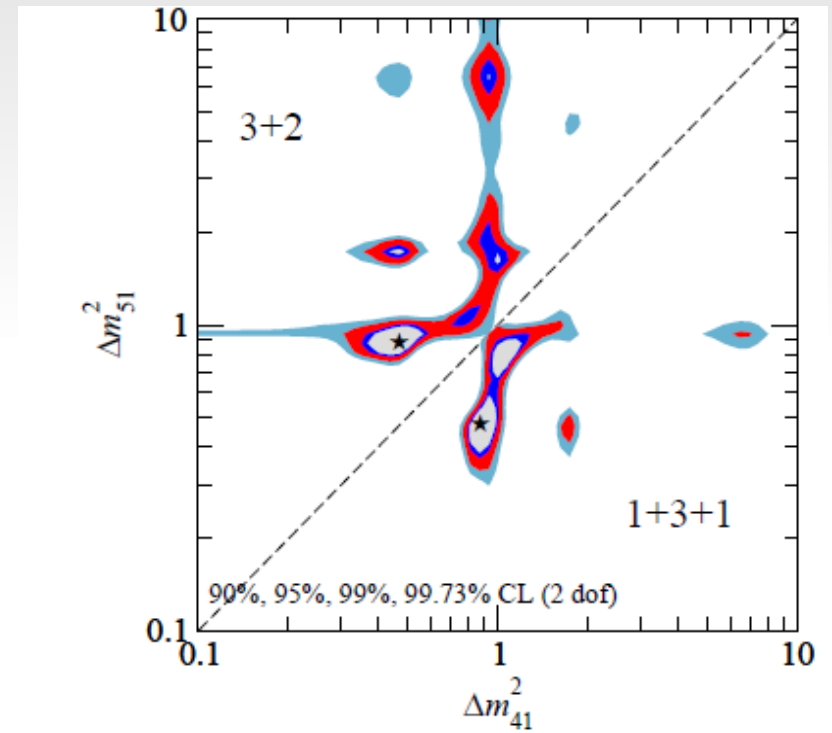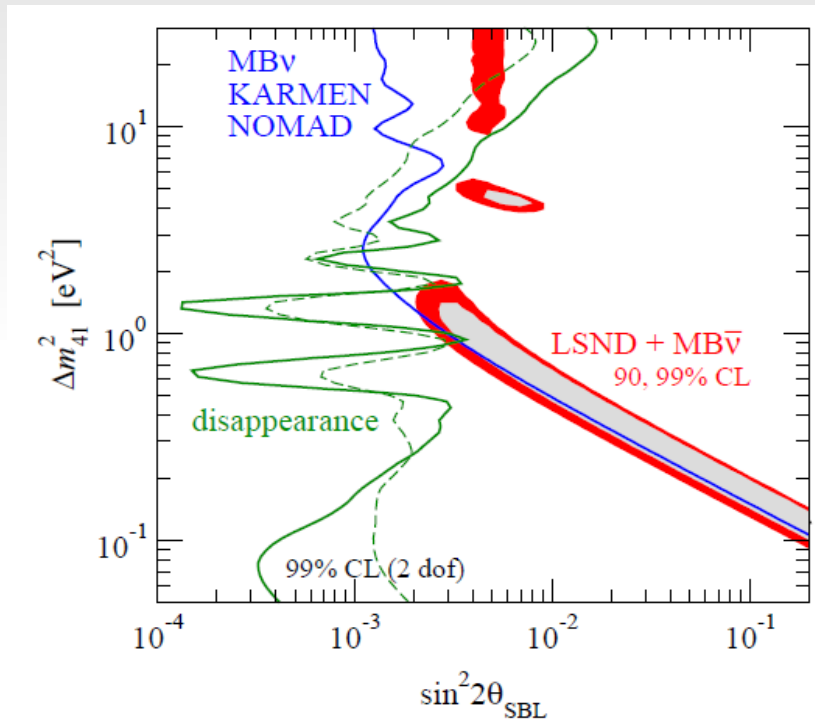
Sterile v is possible

- 3 + 1, 2 steriles:

    v_s mixed with v_e v_μ, as mediators for extra oscillation, plus additional phases for enhanced $\cancel{CP}$.

- 2 + 2 steriles:

    Disfavored by the lack of solar/atmospheric signal (Maltoni, et.al. 2004)

    Sterile: no correction to Z width
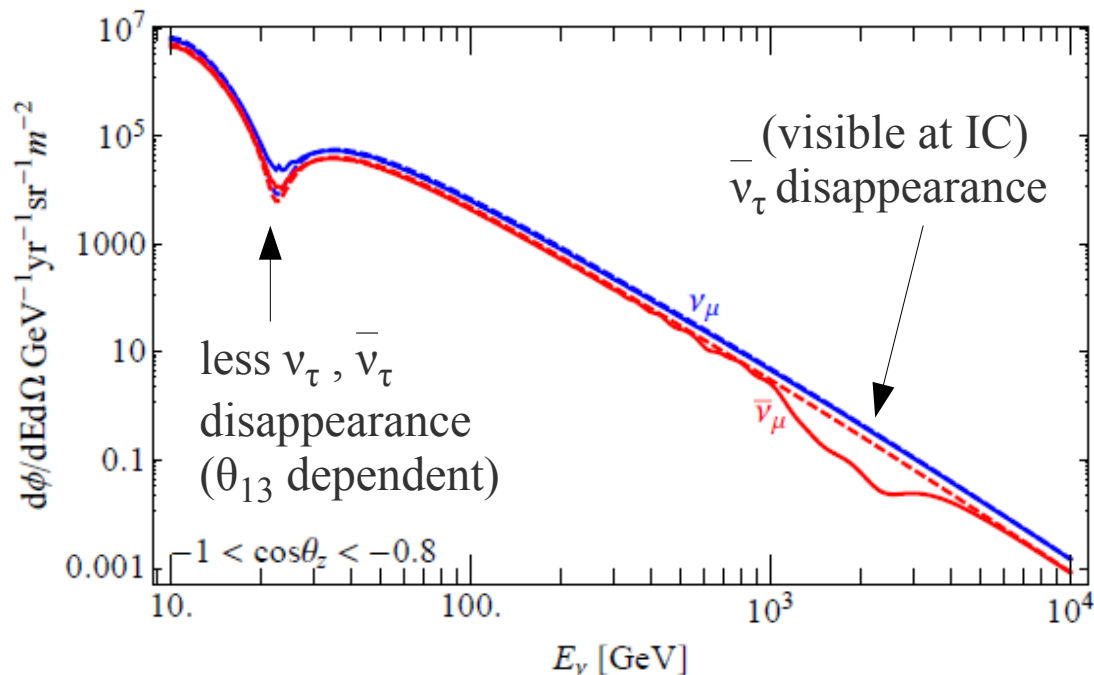   CMB: favors an extra radiation-like species

Global fits with steriles

Kopp, Maltoni, Schwetz (2011):

"one sterile neutrino is not sufficient"

What can IceCube see?

From the upward atmospheric neutrinos

- ~TeV $\nu_\mu(\bar{\nu}_\mu)$ depletion in the energy spectrum

- Distortion in the angular distribution

- Reduced integrated flux? (need good understanding of atm. bkg)

$\Delta m^2_{s1} > 0$

Solid: 3+2 steriles

Dashed: 3 gen only

The 3+2 scenario

- Global 3+2 fits requires at least one Δm^2 at eV^2

- Best-fit point as a sample point

Kopp, Maltoni, Schwetz (2011)

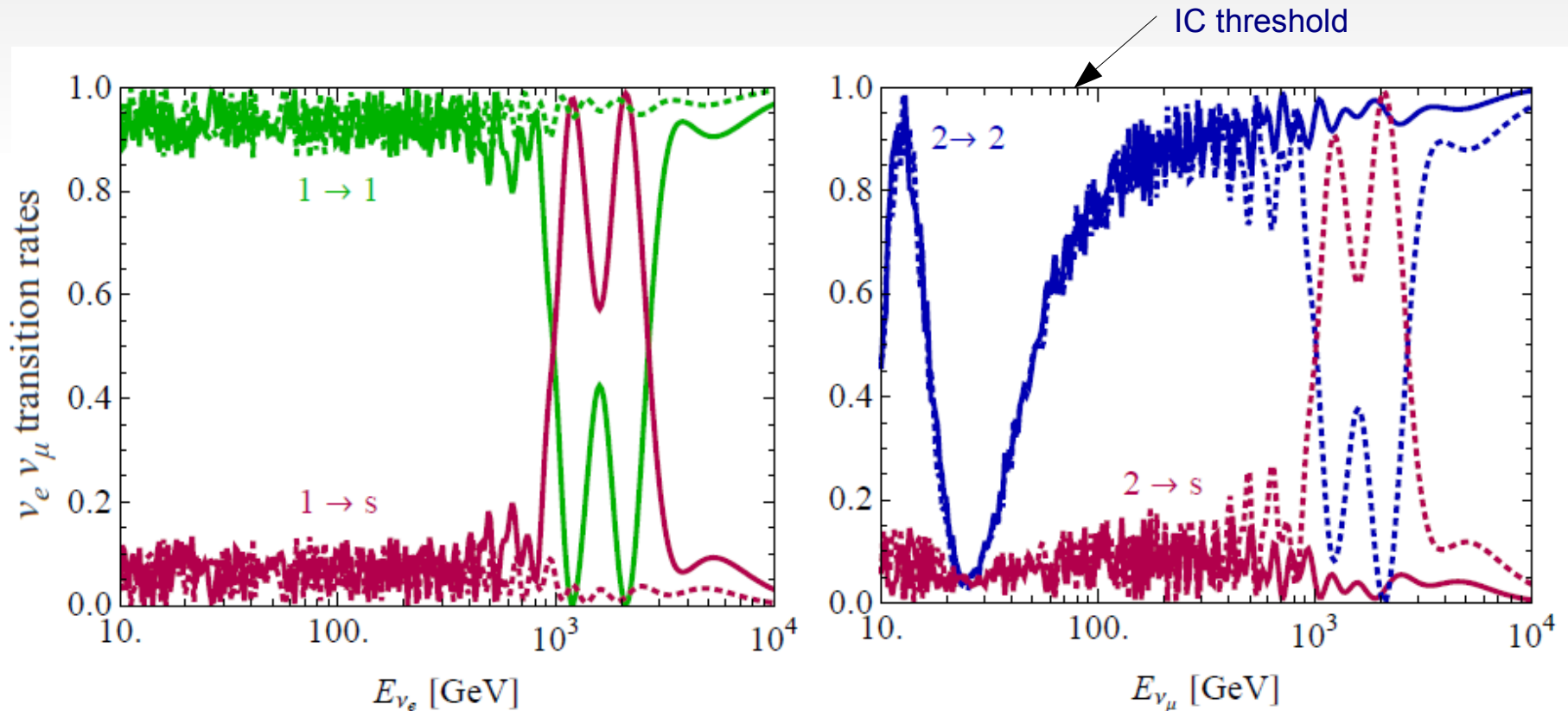|	Δm_{41}^2	$|U_{e4}|$	$|U_{\mu 4}|$	Δm_{51}^2	$|U_{e5}|$	$|U_{\mu 5}|$	δ/π	χ^2/dof
3+2	0.47	0.128	0.165	0.87	0.138	0.148	1.64	110.1/130
1+3+1	0.47	0.129	0.154	0.87	0.142	0.163	0.35	106.1/130

Extended to 5 generations

$$\tilde{\mathbf{H}} = \frac{1}{2E_\nu}\mathbf{U}^* \, \mathbf{diag}\left(0, \delta m_{21}^2, \delta m_{31}^2, \delta m_{41}^2, \delta m_{51}^2\right) \mathbf{U^T}$$
$$\pm \mathbf{diag}(A_{CC} - A_{NC}, -A_{NC}, -A_{NC}, 0, 0)$$

$$\mathbf{U} = \mathcal{R}_{45}\mathcal{R}_{35}\mathcal{R}_{34}\mathcal{R}_{25}\mathcal{R}_{24}\mathcal{R}_{23}\mathcal{R}_{15}\mathcal{R}_{14}\mathcal{R}_{13}\mathcal{R}_{12}$$

$$\mathcal{R}_{ij} = \begin{pmatrix} \cos\theta_{ij} & \sin\theta_{ij}\mathrm{e}^{-i\delta_{ij}} \\ -\sin\theta_{ij}\mathrm{e}^{i\delta_{ij}} & \cos\theta_{ij} \end{pmatrix}$$

# Matter effect inside the Earth

- $\Delta m^2 \sim eV^2 \quad \rightarrow \quad$ resonance oscillation at TeV

- Earth's mantle/core density difference $\rightarrow$ enhanced osc. amplitude

IC threshold

$\nu_e \; \nu_\mu$ transition rates

$1 \rightarrow 1$

$1 \rightarrow s$

E_{ν_e} [GeV]

$2 \rightarrow 2$

$2 \rightarrow s$

E_{ν_μ} [GeV]

s=4,5 for s_1 and s_2 combined,
$\Delta m^2_{s1} > 0$

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Propagation – layered Model

- `Sliced' PREM model: 100 density layers sufficient for >100 GeV
  (anti)neutrinos --- tested against numerical D.E.s

- Near resonance transition rate strongly affected by osc. phase at mantle/core boundaries

For energy < 100 TeV, flux attenuation due to
ν-nucleon collisions can be neglected
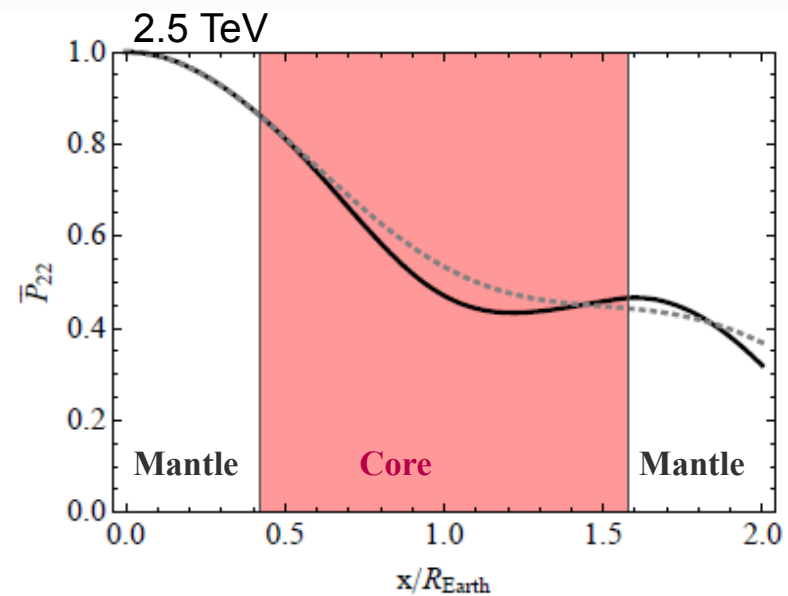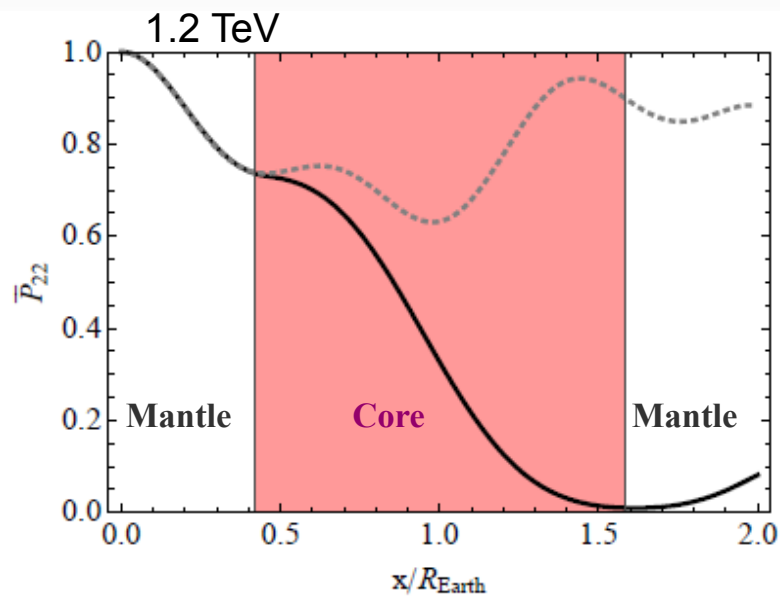
An informative angular distribution

- Impact of increases with the zenith angle
- Higher energy cuts magnify deviation from standard 3 gen.

Integrated ν_μ flux at detector
(averaged over each angular bin width)
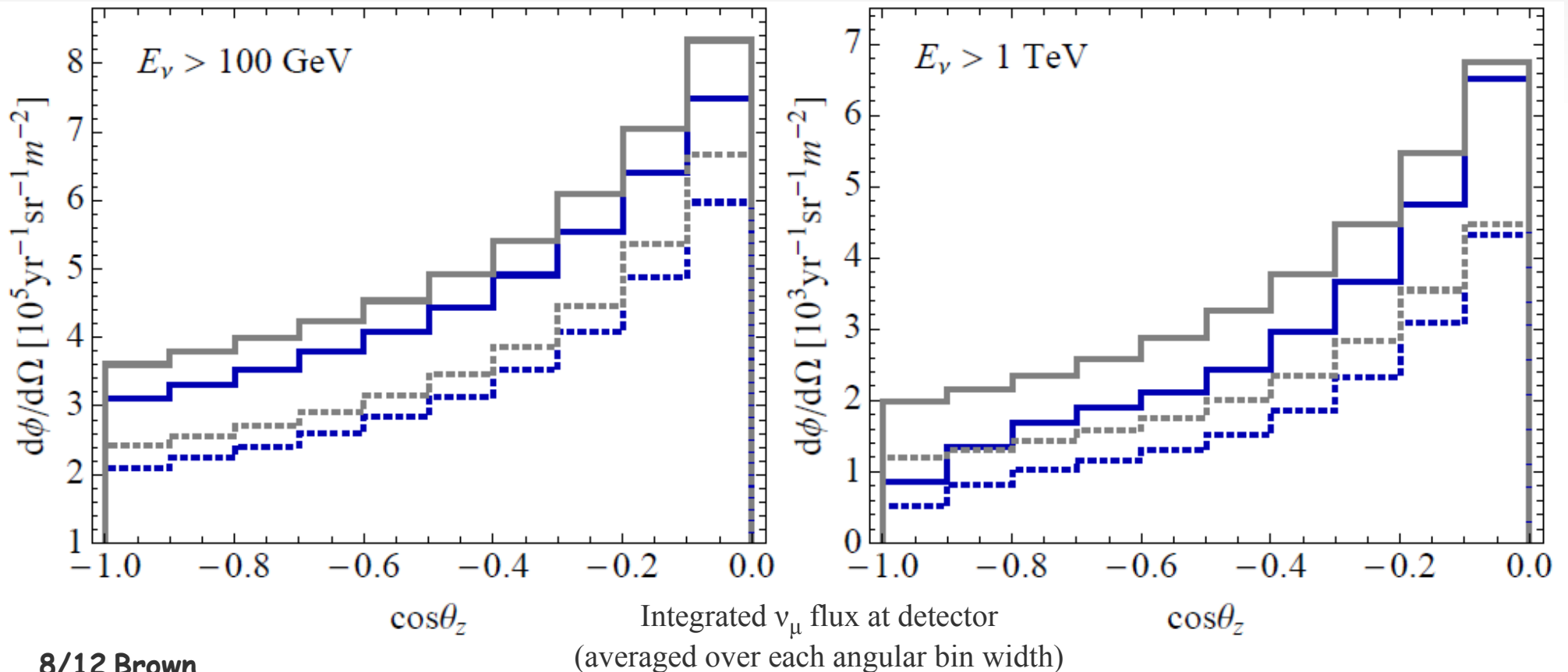
Contained and `up-going' events

- Different ν energy dependence

- Separate A_{eff} for ν and $\bar{\nu}$?

Contained:
track starts inside detector

$$\frac{d\phi_\mu^{con.}}{dE_\mu d\Omega} = V_{eff.}(E_\mu, \theta_z) \int_{E_\mu}^{E_\nu^{max}} dE_\nu \sum_{i=\nu,\bar{\nu}} n_{n/p} \frac{d\sigma_i^{n/p}(E_\nu, E_\mu)}{dE_\mu}$$

$$\cdot \left(P_{12}(E_\nu) \frac{d\phi_\nu^{i,\nu_e}}{dE_\nu} + P_{22}(E_\nu) \frac{d\phi_\nu^{i,\nu_\mu}}{dE_\nu} \right),$$

"Up-going":
track initiates outside detector

$$\frac{d\phi_\mu^{up}}{dE_\mu d\Omega} = A_\mu(E_\mu, \theta_z) \int_0^\infty dz \int_{E_\mu}^{E_\nu} dE_\mu^0 \, P(E_\mu^0, E_\mu; z)$$

$$\cdot \int_{E_\mu}^{E_\nu^{max}} dE_\nu \sum_{i=\nu,\bar{\nu}} n_{n/p} \frac{d\sigma_i^{n/p}(E_\nu, E_\mu^0)}{dE_\mu^0} \left(P_{12}(E_\nu) \frac{d\phi_\nu^{i,\nu_e}}{dE_\nu} + P_{22}(E_\nu) \frac{d\phi_\nu^{i,\nu_\mu}}{dE_\nu} \right)$$

Muon stopping distance increases with E_μ:

"Up-going " event more sensitive to the high energy part of ν_μ spectrum

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Constraint from Angular Distributions

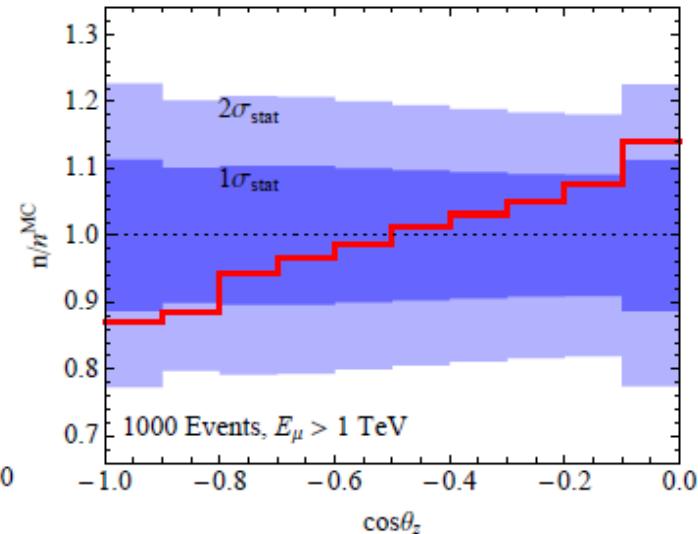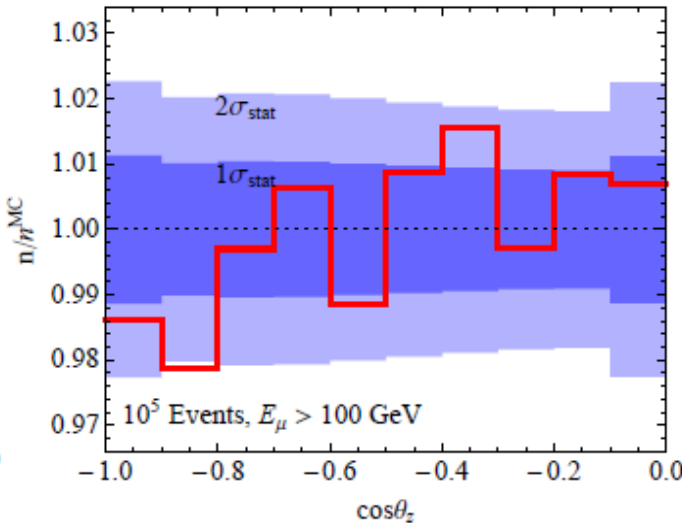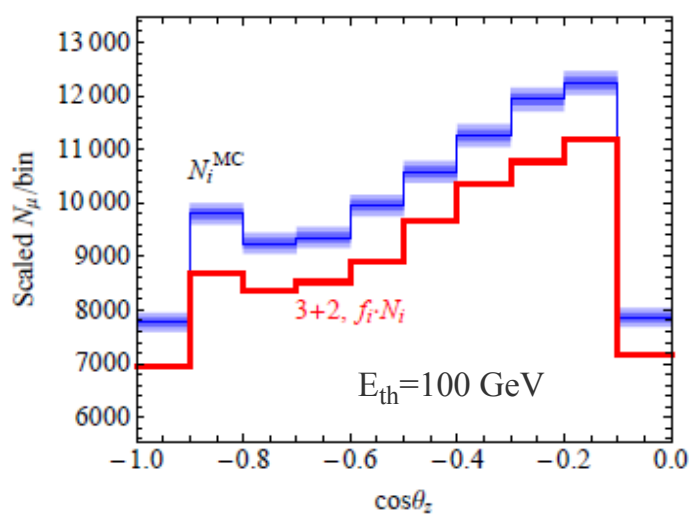- Comparing the "scaled-to-MC" angular distributions:

$$n_i = \frac{f_i N_i}{\sum f_i N_i} \qquad \text{where} \qquad f_i \equiv N_i^{MC}/N_i^{3-gen.}$$

$$x_i = n_i/n_i^{MC} \qquad \text{and} \qquad \delta x_i = x_i \cdot \left(N_i^{MC}\right)^{-1/2}$$

IC 3-gen
Monte Carlo
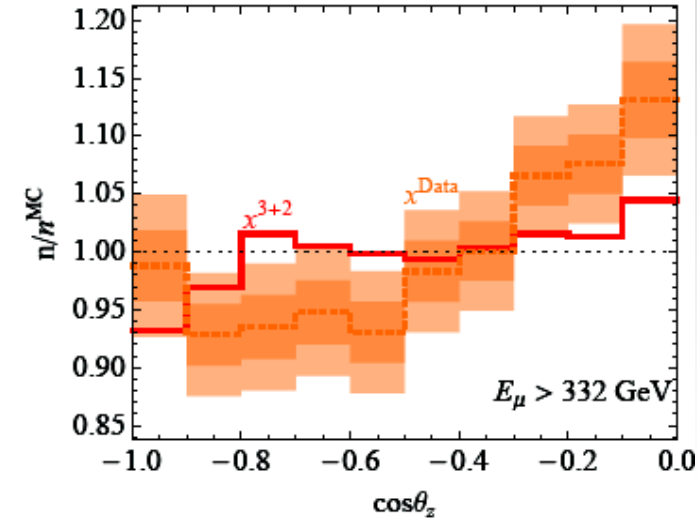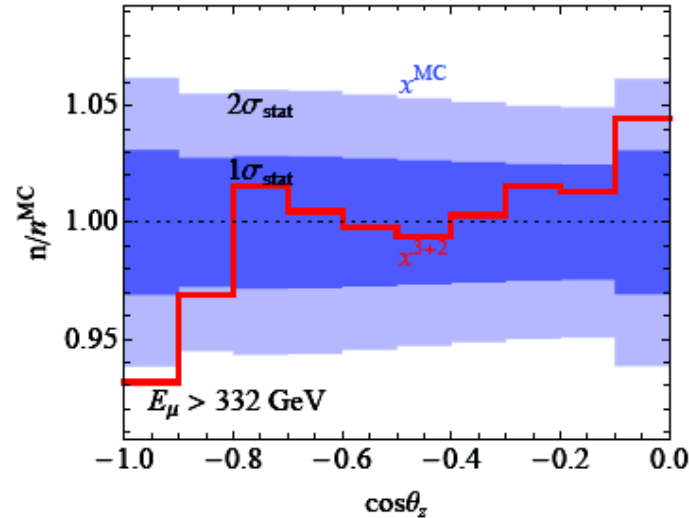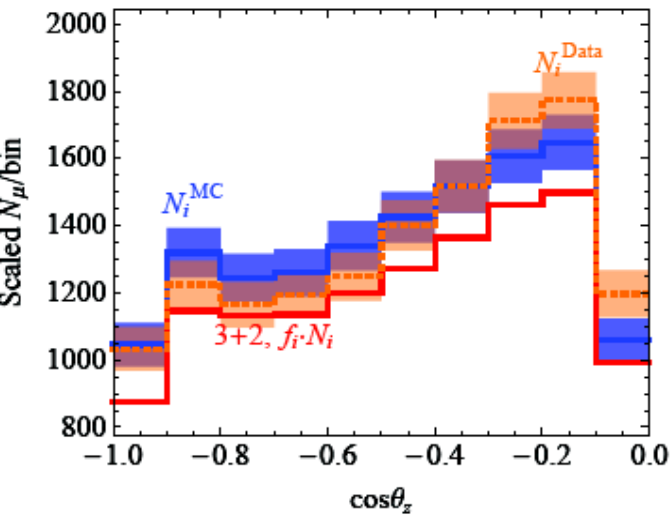(after cuts:
arXiv:1104.5187)

Theoretical
3 gen prediction

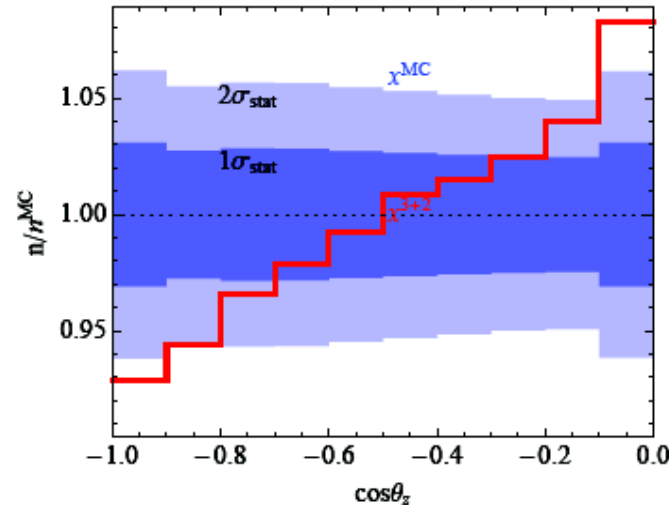Prospects of 10^5 contained
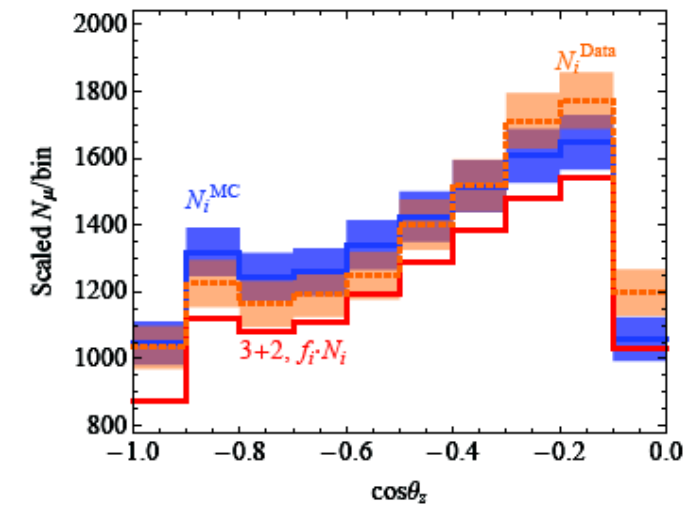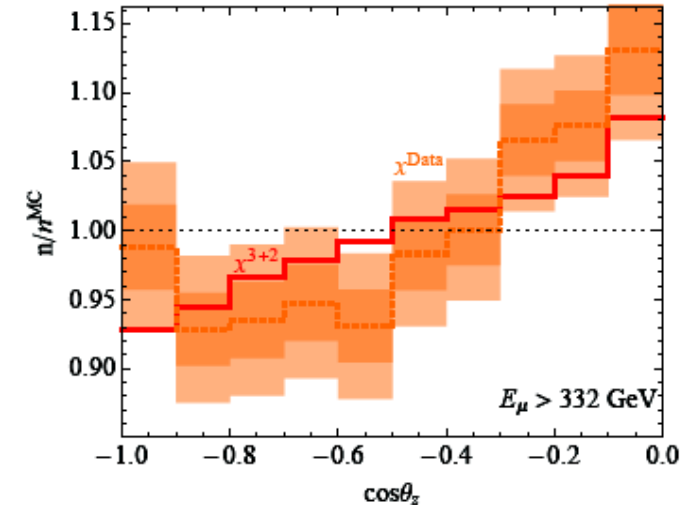events, [E_{th}=100 GeV]:
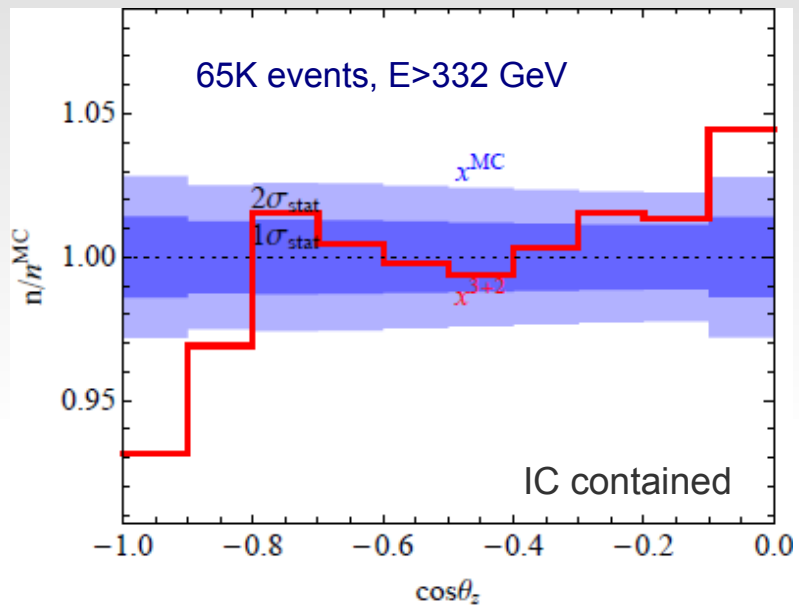
40-string atm. data (2008-2009)

Assuming 100% contained:

Assuming 100% up(through)-going* :

*A_{eff} from Gonzalez-Garcia, 2009

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Vertical & horizontal bins may have large systematics
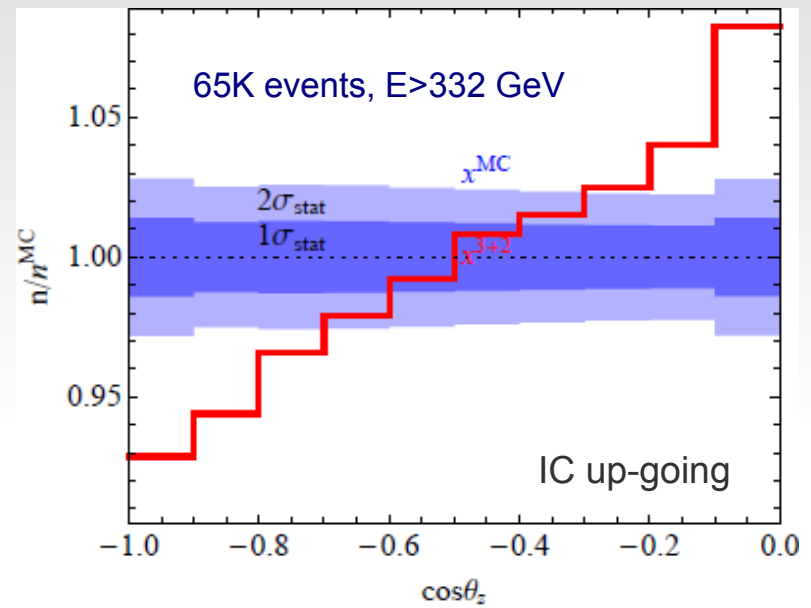
5 year data?

IC contained

*IC "up-going"

Summary

- A generic test of $\Delta m^2 \sim eV^2$ oscillation at IceCube

- Visibly large deviation (from 3 gen.) in the muon angular distribution

- Improved statistics will offer strong constraint by future IC data release

Stay tuned!