Possible new physics through search for unitarity violation

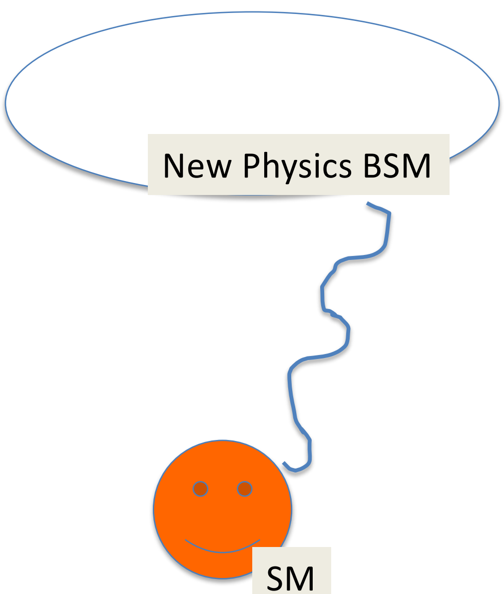
Hisakazu Minakata, Center for Neutrino Physics, Virginia Tech

With: Chee Sheng Fong, Hiroshi Nunokawa, Ivan Martinez-Soler, Peter Denton

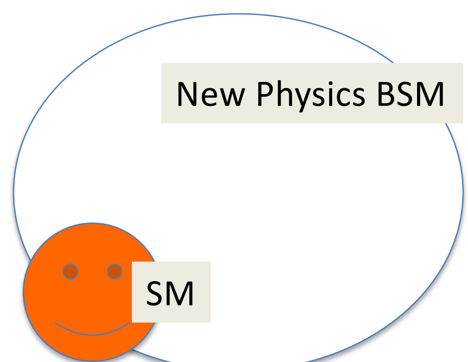
My starting point was..

- How can we conclude the neutrino story if high-scale seesaw is nature designed ?
- Unitarity test at super-high precision..
- But, I learned SU(2) x U(1) prevail at high scale, Charge lepton constraints more powerful

High scale unitarity violation



Low scale unitarity violation



High- vs low-scale unitarity violation: more generic differences

High-scale UV >> m_W	Low-scale UV << m_W
lepton flavor universality: NO	lepton flavor universality: YES
zero distance neutrino flavor transition: YES	zero distance neutrino flavor transition: NO
"Model-independent" formalism = integrate out high-E NP	Model-independent" formalism?

A big difference between High-scale and Low-scale UV is: SU(2)xU(1) at high-scale UV new physics → Severer constraints from charged lepton sector

Model independent framework in low-scale UV?

It looks hard..

- How to integrate various scenarios of BSM physics at low energies ?
- Not obvious…
- My style now is: Let try one by one
- Yet, I want to avoid # of trial = # of models
- So we started “general sterile” = (3+N) model = “indep of details of sterile sector” (with C.-Sheng Fong and H. Nunokawa)

Fong, HM, Nunokawa
JHEP2017, JHEP2019

3-active + N-sterile unitary model

3 active +N sterile unitary model in vacuum

My previous N matrix = U now.....3x3

Schechter-Valle, PRD1980

$$\nu_\alpha = \mathbf{U}_{\alpha i}\tilde{\nu}_i,$$

$$i\frac{d}{dx}\nu = H\nu.$$

$$\mathbf{U} = \begin{bmatrix} U & W \\ Z & V \end{bmatrix}$$

NxN

$$H = \mathbf{U} \begin{bmatrix} \Delta_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & \Delta_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & \Delta_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & \Delta_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & 0 & 0 & \Delta_{3+N} \end{bmatrix} \mathbf{U}^\dagger$$

$$\Delta_i \equiv \frac{m_i^2}{2E} \quad (i = 1, 2, 3), \qquad \Delta_J \equiv \frac{m_J^2}{2E} \quad (J = 4, \cdots, 3+N).$$

We try fast oscillation averaged out regime for "model-independent" framework for low-scale UV

Probability in vacuum

$$P(\nu_\beta \to \nu_\alpha) = \left|\sum_{k=1}^{3} U_{\alpha k} U^*_{\beta k}\right|^2 \qquad (4.5)$$

$$-2\sum_{j\neq k} \mathrm{Re}\left(U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k}\right) \sin^2 \frac{(\Delta_k - \Delta_j)x}{2} + \sum_{j\neq k} \mathrm{Im}\left(U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k}\right) \sin(\Delta_k - \Delta_j)x$$

$$+\sum_J |W_{\alpha J}|^2 |W_{\beta J}|^2$$

What is this?

$$+\sum_{J\neq K}\left[\mathrm{Re}\left(W^*_{\alpha J} W_{\beta J} W_{\alpha K} W^*_{\beta K}\right)\cos(\Delta_K - \Delta_J)x + \mathrm{Im}\left(W^*_{\alpha J} W_{\beta J} W_{\alpha K} W^*_{\beta K}\right)\sin(\Delta_K - \Delta_J)x\right]$$

$$+2\sum_{j=1}^{3}\sum_{K=4}^{3+N}\left[\mathrm{Re}\left(U^*_{\alpha j} U_{\beta j} W_{\alpha K} W^*_{\beta K}\right)\cos(\Delta_K - \Delta_j)x + \mathrm{Im}\left(U^*_{\alpha j} U_{\beta j} W_{\alpha K} W^*_{\beta K}\right)\sin(\Delta_K - \Delta_j)x\right].$$

- Active-active, active-sterile, sterile-sterile oscillations
- If Δm^2_{as} (Δm^2_{ss}) > 0.1 eV^2, "fast oscillation" due to active-sterile and sterile-sterile Δm^2 are averaged out

$$\left\langle \sin\left(\frac{\Delta m^2_{Ji} x}{2E}\right)\right\rangle \approx \left\langle \sin\left(\frac{\Delta m^2_{JK} x}{2E}\right)\right\rangle \approx 0,$$

P looks almost standard one, but there is a P leaking term

Both 4th order in W, have to be kept!

Probability leakage !

Appearance

$$P(\nu_\beta \to \nu_\alpha) = \mathcal{C}_{\alpha\beta} + \left| \sum_{j=1}^{3} U_{\alpha j} U^*_{\beta j} \right|^2 - 2 \sum_{j \neq k} \mathrm{Re}\left(U_{\alpha j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k} \right) \sin^2 \frac{(\Delta_k - \Delta_j) x}{2}$$
$$- \sum_{j \neq k} \mathrm{Im}\left(U_{\alpha j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k} \right) \sin(\Delta_k - \Delta_j) x,$$

U = non-unitary “MNS”

Disappearance

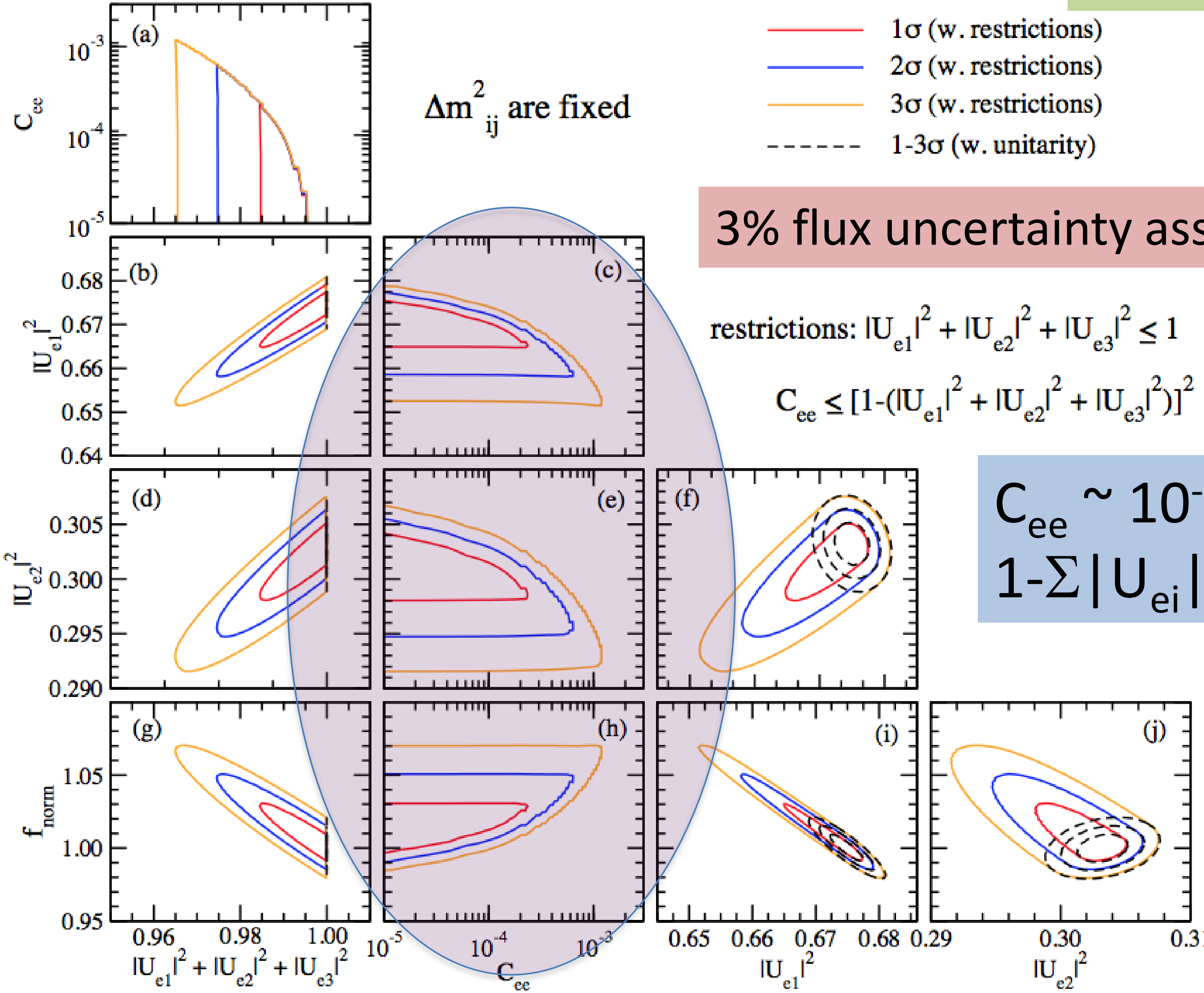
$$P(\nu_\alpha \to \nu_\alpha) = \mathcal{C}_{\alpha\alpha} + \left(\sum_{j}^{3} |U_{\alpha j}|^2 \right)^2 - 4 \sum_{k>j}^{3} |U_{\alpha j}|^2 |U_{\alpha k}|^2 \sin^2 \frac{(\Delta_k - \Delta_j) x}{2},$$

$$\mathcal{C}_{\alpha\beta} \equiv \sum_{J=1}^{N} |W_{\alpha J}|^2 |W_{\beta J}|^2, \qquad \mathcal{C}_{\alpha\alpha} \equiv \sum_{J=1}^{N} |W_{\alpha J}|^4$$

Order ~ W^4, small!!

Sensitivity to C_{ee} and $1-\Sigma|U_{ei}|^2$ from JUNO 5 years

Fong, HM, Nunokawa JHEP2017



3% flux uncertainty assumed

restrictions: $|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 \leq 1$

$C_{ee} \leq [1-(|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2)]^2$

$C_{ee} \sim 10^{-4}$ (1 σ)

$1-\Sigma|U_{ei}|^2 \sim 0.01$

In matter? A long story…

One page summary here!

A simple formula for oscillation probability in matter w/o unitarity: leading order in W perturbation

$$P(\nu_\beta \to \nu_\alpha) = \mathcal{C}_{\alpha\beta} + \left| \sum_{j=1}^{3} U_{\alpha j} U^*_{\beta j} \right|^2$$

$$- 2 \sum_{j \neq k} \text{Re}\left[(UX)_{\alpha j} (UX)^*_{\beta j} (UX)^*_{\alpha k} (UX)_{\beta k} \right] \sin^2 \frac{(h_k - h_j)x}{2}$$

$$- \sum_{j \neq k} \text{Im}\left[(UX)_{\alpha j} (UX)^*_{\beta j} (UX)^*_{\alpha k} (UX)_{\beta k} \right] \sin(h_k - h_j)x,$$

X=...

$$\mathbf{U} = \begin{bmatrix} U & W \\ Z & V \end{bmatrix}$$

- All W^2 & W^4 terms avaraged out or suppressed if $\Delta m^2 > 0.1$ eV^2 except for P leaking term!!
- UV effect is in: (1) explicit W correction term, (2) non-unitary U matrix

Fong, HM, Nunokawa JHEP2019

$$\left|S^{(2)}_{\alpha\beta}\right|^2_{\rm 1st} = \sum_{k,K}\sum_{l,L} \frac{1}{(\Delta_K - h_k)(\Delta_L - h_l)}$$

$$\times \left[x^2 e^{-i(h_k - h_l)x} - (ix)\frac{e^{-i(\Delta_K - h_l)x} - e^{-i(h_k-h_l)x}}{(\Delta_K - h_k)} + (ix)\frac{e^{-i(h_k-\Delta_L)x} - e^{-i(h_k-h_l)x}}{(\Delta_L - h_l)} \right.$$

$$\left. + \frac{1}{(\Delta_K - h_k)(\Delta_L - h_l)} \left\{ e^{-i(\Delta_K - \Delta_L)x} + e^{-i(h_k-h_l)x} - e^{-i(\Delta_K - h_l)x} - e^{-i(h_k - \Delta_L)x} \right\} \right]$$

$$\times (UX)_{\alpha k}(UX)^*_{\beta k} \left\{(UX)^\dagger A W\right\}_{kK} \left\{W^\dagger A (UX)\right\}_{Kk}$$

$$\times (UX)^*_{\alpha l}(UX)_{\beta l} \left\{(UX)^\dagger A W\right\}_{lL} \left\{W^\dagger A (UX)\right\}_{Ll}$$

$$+ \sum_{k\neq m}\sum_{K}\sum_{l\neq n}\sum_{L} \frac{1}{(h_m - h_k)(\Delta_K - h_k)(\Delta_K - h_m)} \frac{1}{(h_n - h_l)(\Delta_L - h_l)(\Delta_L - h_n)}$$

$$\times \left[(\Delta_K - h_k)\, e^{-ih_m x} - (\Delta_K - h_m)\, e^{-ih_k x} - (h_m - h_k) e^{-i\Delta_K x} \right]$$

$$\times \left[(\Delta_L - h_l)\, e^{+ih_n x} - (\Delta_L - h_n)\, e^{+ih_l x} - (h_n - h_l) e^{+i\Delta_L x} \right]$$

$$\times (UX)_{\alpha k}(UX)^*_{\beta m} \left\{(UX)^\dagger A W\right\}_{kK} \left\{W^\dagger A (UX)\right\}_{Km}$$

$$\times (UX)^*_{\alpha l}(UX)_{\beta n} \left\{(UX)^\dagger A W\right\}_{nL} \left\{W^\dagger A (UX)\right\}_{Ll}$$

$$+ \sum_{k,K}\sum_{l,L} \frac{1}{(\Delta_K - h_k)(\Delta_L - h_l)} \left(e^{-i\Delta_K x} - e^{-ih_k x}\right)\left(e^{+i\Delta_L x} - e^{+ih_l x}\right)$$

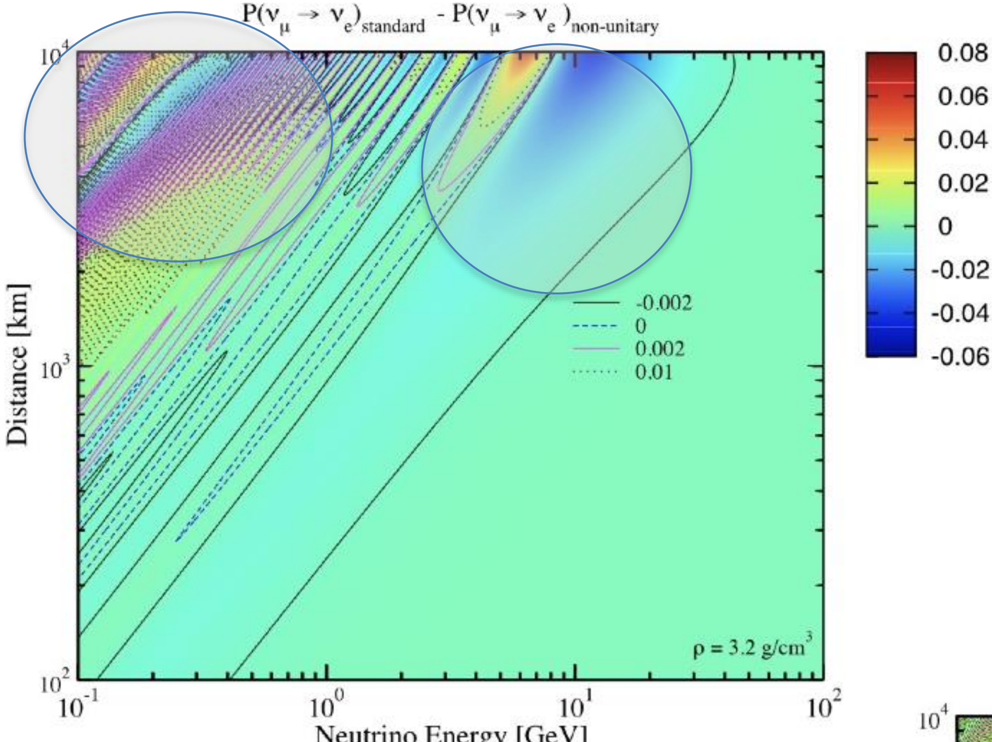
$$\times \left[(UX)_{\alpha k} W^*_{\beta K} \left\{(UX)^\dagger A W\right\}_{kK} + W_{\alpha K}(UX)^*_{\beta k} \left\{W^\dagger A (UX)\right\}_{Kk} \right]$$

$$\times \left[(UX)^*_{\alpha l} W_{\beta L} \left\{W^\dagger A (UX)\right\}_{Ll} + W^*_{\alpha L}(UX)_{\beta l} \left\{(UX)^\dagger A W\right\}_{lL} \right]$$

$$+ \sum_{K} |W_{\alpha K}|^2 |W_{\beta K}|^2 + \sum_{K\neq L} e^{-i(\Delta_K - \Delta_L)x} W_{\alpha K} W^*_{\beta K} W^*_{\alpha L} W_{\beta L}. \qquad \text{(C.1)}$$

Looking for P leaking term in W^4 terms…

Here is !!

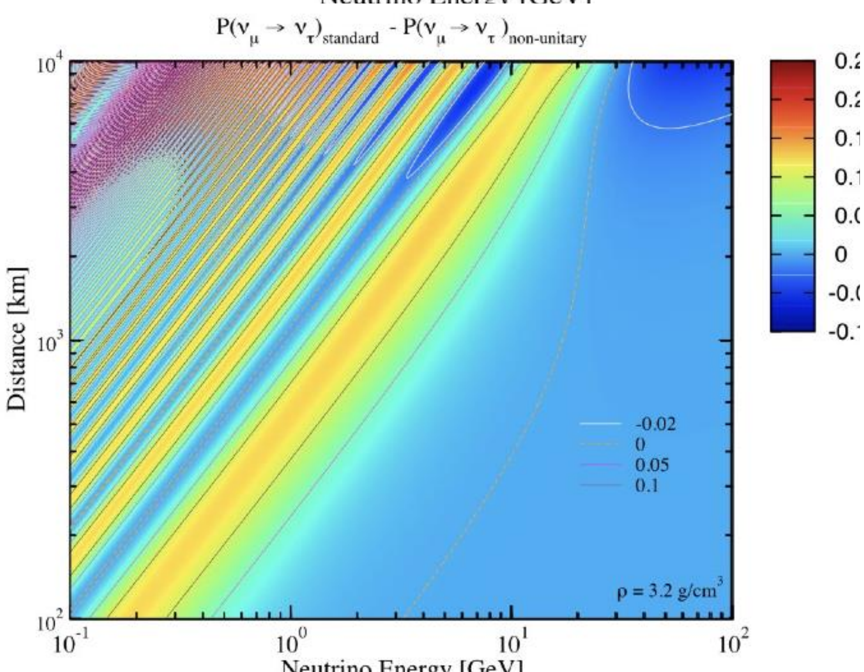


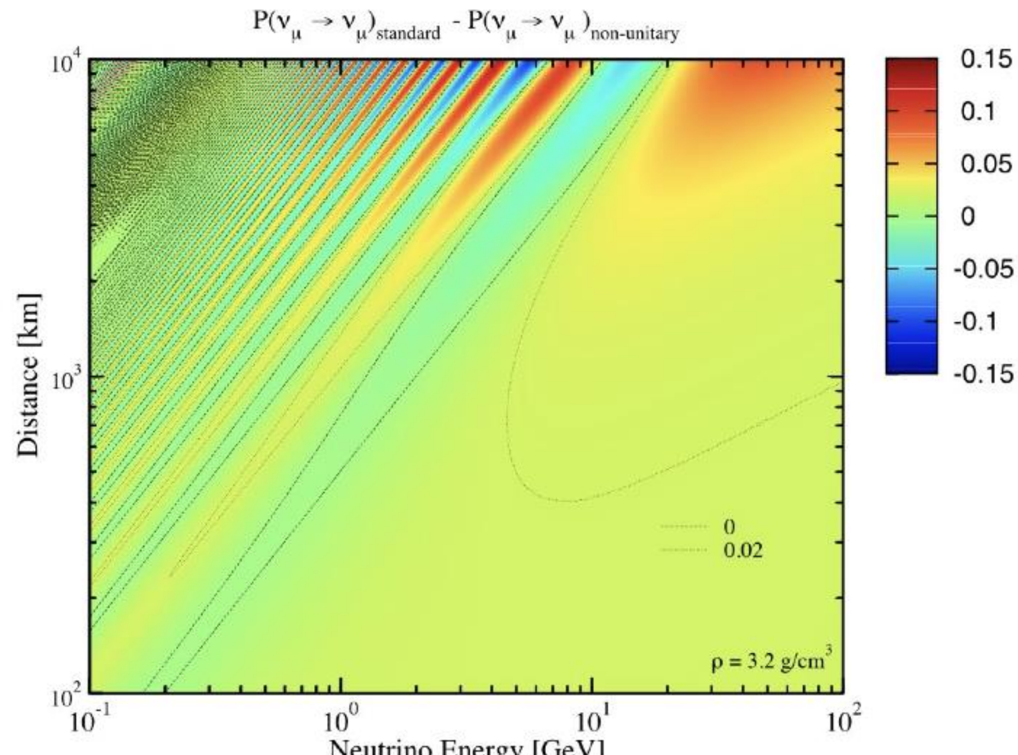
- Leading order terms = Zeroth order in W

ΔP large at solar- and atm-MSW enhanced regions

$\alpha_{11} = 0.990,\ \alpha_{21} = -0.0141,\ \alpha_{22} = 0.995,\ \alpha_{31} = -0.0445,$

$\alpha_{32} = -0.0316,\ \alpha_{33} = 0.949.$





Leading order in W expansion: our current status

α parametrization (δ vs. α correlation)

Alpha parametrization

$$N = (1-\alpha)U = \left\{1 - \begin{bmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & \alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & \alpha_{\tau\tau} \end{bmatrix}\right\} U$$

$e^{-i\delta}\alpha_{\mu e}$, $\alpha_{\tau e}$, and $e^{i\delta}\alpha_{\tau\mu}$,

Let us call "canonical phase combination"

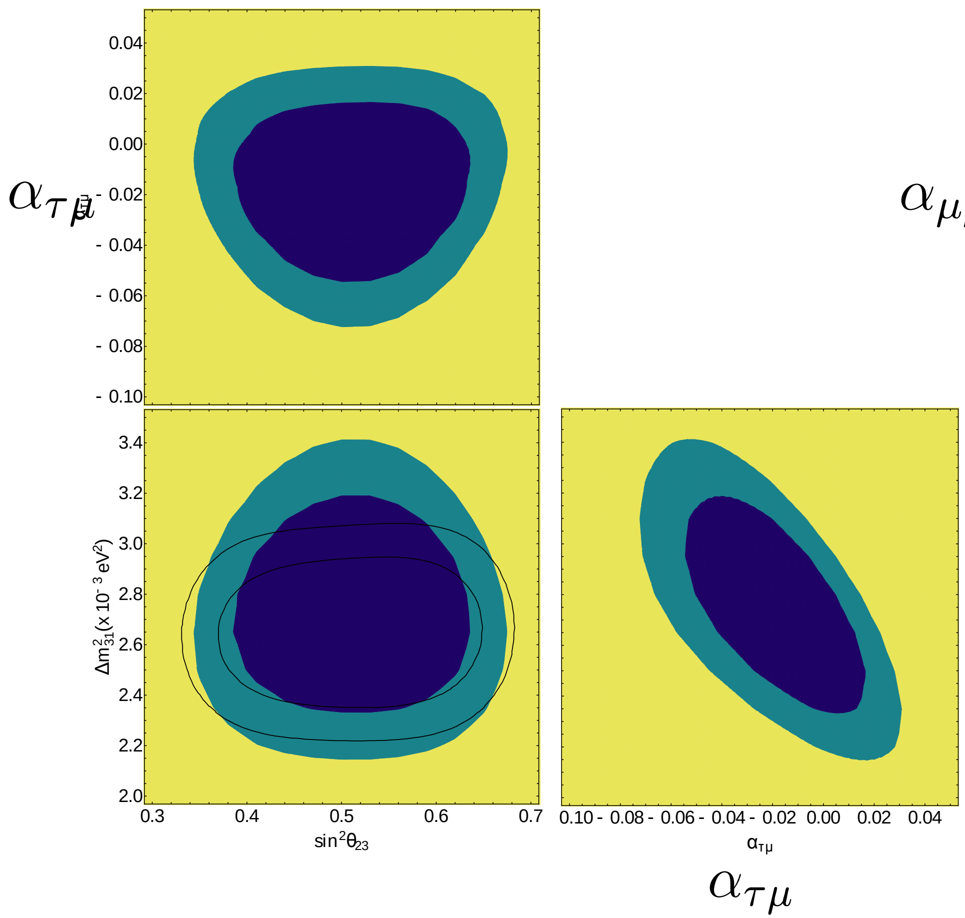
δ and alpha always come in this combination!

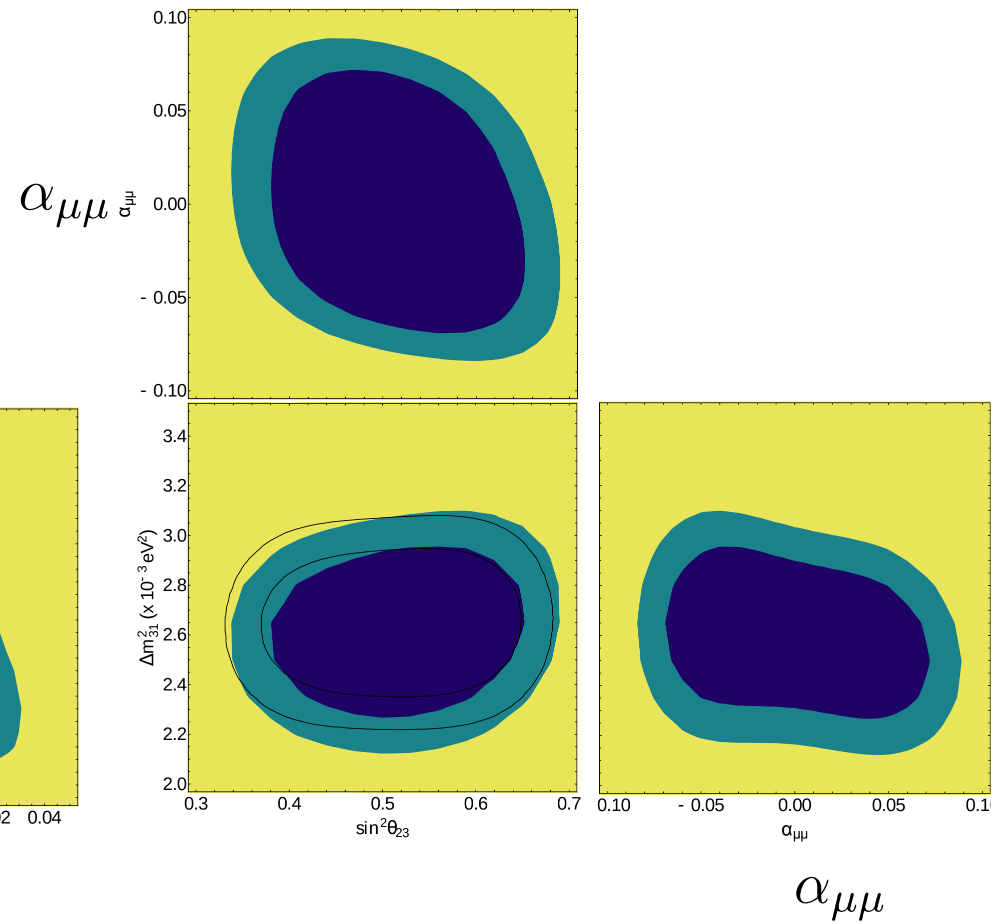
Ivan Martinez-Soler, HM, arXiv:1806.10152

Deep Core 2011-14 (3years, 6-60 GeV)

−0.07 < ατμ ~< 0.03,
|αμμ | ~< 0.08

20% flux normalization error

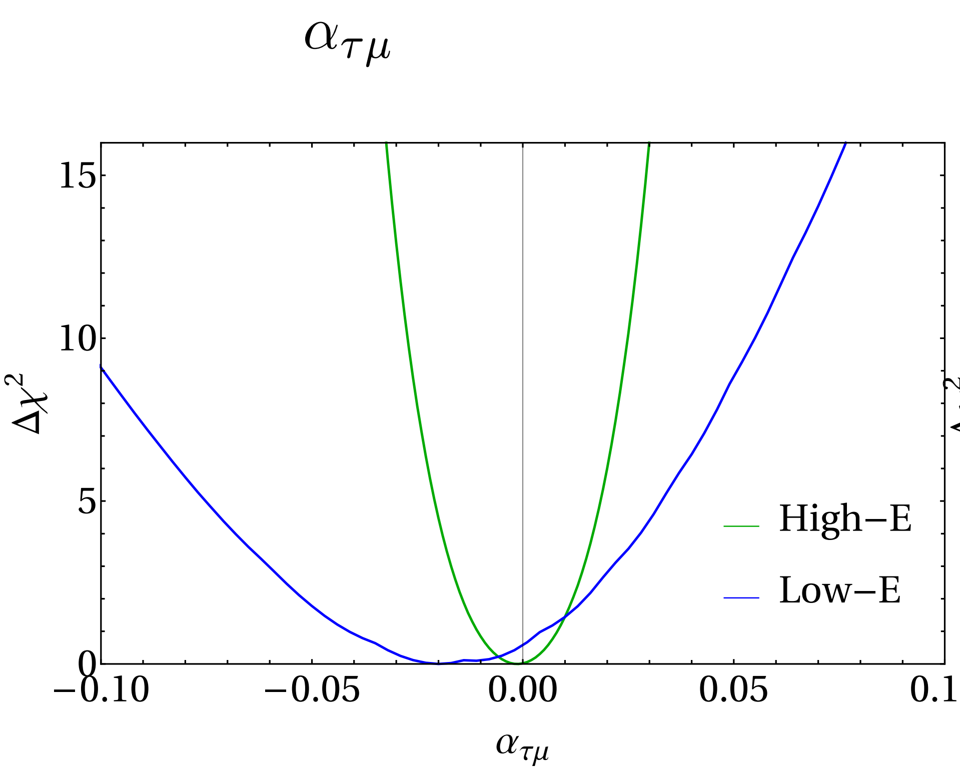


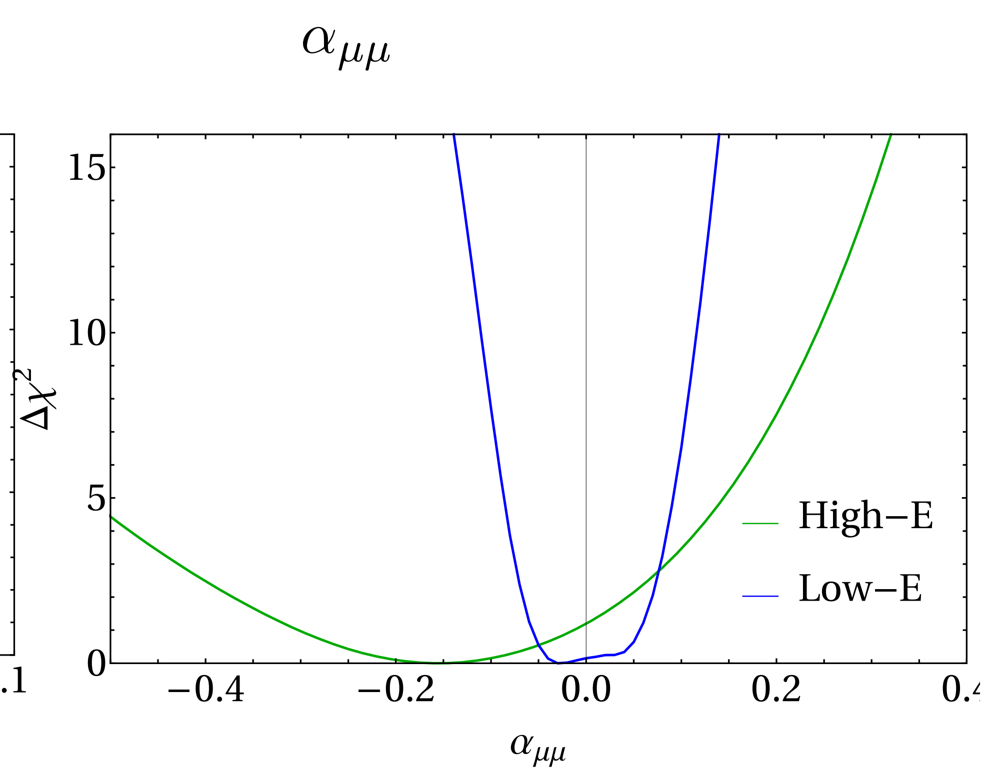


Peter Denton, Ivan Martinez-Soler, HM, to appear

IceCube (1 year)
(400 GeV-20 TeV) vs DeepCore

50% flux normalization error





For α_τμ (α_μμ) high-E (low E) is more constraining

Peter Denton, Ivan Martinez-Soler, HM, to appear

Second order corrections: characteristic to low-scale UV

Hunting W^2 terms: need theory…

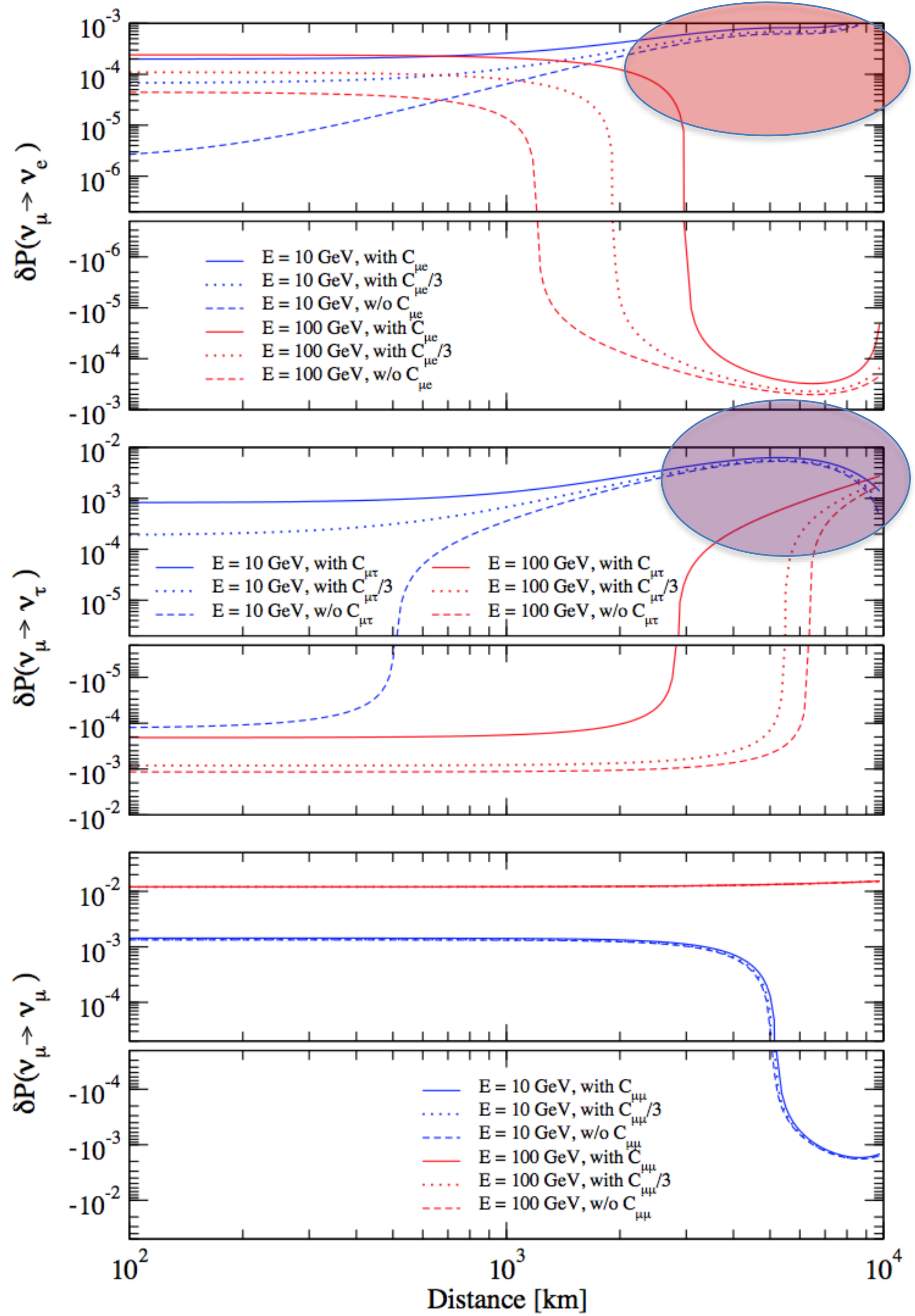
$$\delta_{\alpha\beta} = \sum_{j=1}^{3} U_{\alpha j} U^*_{\beta j} + \sum_{J=4}^{N+3} W_{\alpha J} W^*_{\beta J}.$$

$$\begin{aligned}
& P(\nu_\beta \to \nu_\alpha)^{(0+2)} \\
&= \left| \sum_{j=1}^{3} U_{\alpha j} U^*_{\beta j} \right|^2 - 2 \sum_{j \neq k} \text{Re} \left[(UX)_{\alpha j} (UX)^*_{\beta j} (UX)^*_{\alpha k} (UX)_{\beta k} \right] \sin^2 \frac{(h_k - h_j)x}{2} \\
&- \sum_{j \neq k} \text{Im} \left[(UX)_{\alpha j} (UX)^*_{\beta j} (UX)^*_{\alpha k} (UX)_{\beta k} \right] \sin(h_k - h_j)x \\
&+ 2\text{Re} \Bigg\{ \sum_m \sum_{k,K} \frac{1}{\Delta_K - h_k} \left[(ix) e^{-i(h_k - h_m)x} - \frac{e^{-i(h_k - h_m)x}}{(\Delta_K - h_k)} \right] \\
&\times (UX)_{\alpha k} (UX)^*_{\beta k} (UX)^*_{\alpha m} (UX)_{\beta m} \left\{ (UX)^\dagger A W \right\}_{kK} \left\{ W^\dagger A (UX) \right\}_{Kk} \\
&- \sum_m \sum_{k \neq l} \sum_K \frac{1}{(h_l - h_k)(\Delta_K - h_k)(\Delta_K - h_l)} \\
&\times \left[(\Delta_K - h_k)\, e^{-i(h_l - h_m)x} - (\Delta_K - h_l)\, e^{-i(h_k - h_m)x} \right] \\
&\times (UX)_{\alpha k} (UX)^*_{\beta l} (UX)^*_{\alpha m} (UX)_{\beta m} \left\{ (UX)^\dagger A W \right\}_{kK} \left\{ W^\dagger A (UX) \right\}_{Kl} \\
&- \sum_m \sum_{k,K} \frac{e^{-i(h_k - h_m)x}}{(\Delta_K - h_k)} \Bigg[(UX)_{\alpha k} W^*_{\beta K} (UX)^*_{\alpha m} (UX)_{\beta m} \left\{ (UX)^\dagger A W \right\}_{kK} \\
&+ W_{\alpha K} (UX)^*_{\beta k} (UX)^*_{\alpha m} (UX)_{\beta m} \left\{ W^\dagger A (UX) \right\}_{Kk} \Bigg] \Bigg\}, \qquad (3.46)
\end{aligned}$$

W2 corrections

small in most of the regions of L-E, but sizeable in limited places

- Peculiar zenith angle dep
- High energy, long baseline → IceCube, PINGU, Hyper-K



Conclusion

- I introduced UV scenarios, at high-scale and low-scale
- Low-scale UV = relatively new, nu experiments play a role, yet no systematic way of "integrating out" new physics sector

→ (3+N) unitary model examined

→ new terms appeared: P-leaking constant + W^2 correction terms

→ Probably they are "model-indep" features of low-scale UV