STANDARD MODEL FLAVOR FROM AN SU(2) SYMMETRY

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Based on arXiv:1611.07033 (Accepted to PRD)

Flavor & Symmetries

Continuous vs. Discrete (extensive literature on each!)

- First attempts in the 1970s – *horizontal symmetry*

Prog. Theor. Phys. ***60*** *, 822 (1978); T. Maehara and T. Yanagida*
Phys. Rev. Lett. ***42*** *, 421 (1979); F. Wilczek & A. Zee*
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- Minimal Flavor Violation (MFV)

– *When masses → 0, SM has* $U(3)^5$ *symmetry*
– *Yukawa matrices as spurions – dynamical origin?*
– *Small flavor-changing neutral currents (FCNCs)*

Phys. Lett. ***B****188, 99 (1987); R.S. Chivukula & H. Georgi*
hep-ph/0207036; G. D'Ambrosio, et al.
hep-ph/0507001; V. Cirigliano, et al.
arXiv:1103.2915; R. Alonso, et al.

Flavorspin

Central Hypotheses:

1.) SM flavor is derived from a single $SU(2)$ symmetry under which all fermions are charged:

$$Q_L,\ u_R,\ d_R,\ L_L,\ e_R \sim \mathbf{3}$$

2.) The fundamental spurions transform according to representations of this group:

$$Y_3 \sim \mathbf{3} \qquad\qquad Y_5 \sim \mathbf{5}$$

arXiv:1611.07033; J.B. & D. Hernández

Formalism

The fundamental spurions:

$$Y_3 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -1 & 0 \end{pmatrix} \quad Y_5 = \begin{pmatrix} y_{11} & y_{12} & y_{13} \\ y_{12} & y_{22} & y_{23} \\ y_{13} & y_{23} & -(y_{11} + y_{22}) \end{pmatrix}$$

Yukawa Lagrangian:

$$-\mathcal{L}_{\mathrm{Yuk}} \supset \overline{Q_L} Y_u u_R \cdot \widetilde{H} + \overline{Q_L} Y_d d_R \cdot H + \overline{L_L} Y_l e_R \cdot H + h.c.$$

The Yukawa matrices:

$$Y_X = \mu_X \left[i Y_3 + \left(1 - \xi_X\right) Y_3^2 + \varepsilon_X Y_5 + \delta_X \mathbb{I} \right]$$

The Quark Sector

Masses (at leading order):

$$y_{X1}^2 = 0 \qquad y_{X2}^2 = \mu_X^2 |\xi_X|^2 \qquad y_{X3}^2 = \mu_X^2 |2 - \xi_X|^2$$

Mixing Matrix (perturbative):

$$V_{XL} Y_X V_{XR}^\dagger = \mathrm{diag}\{y_{X1}, y_{X2}, y_{X3}\}; \quad V_{\mathrm{CKM}} = V_{uL} V_{dL}^\dagger$$

$$\boxed{\frac{\sin\theta_{13}^q}{\sin\theta_{23}^q} \sim \left|\frac{y_{12} + i\, y_{13}}{y_{22} + i\, y_{23}}\right| \sim 10^{-1}} \qquad \boxed{\frac{\sin\theta_{12}^q}{\sin\theta_{13}^q} \sim \frac{1}{|\xi_d|} \sim 10^2}$$

The Lepton Sector

Charged leptons similar to the quarks – but *neutrinos*?

<u>Dirac Neutrinos:</u>

$$-\mathcal{L}_{\mathrm{Yuk}} \supset \overline{L_L} Y_\nu N_R \cdot \widetilde{H} + h.c.$$

$$Y_\nu = \mu_\nu \left[i Y_3 + \left(1 - \xi_\nu\right) Y_3^2 + \varepsilon_\nu Y_5 + \delta_\nu \mathbb{I} \right]$$

- Masses form NH, at leading order: $\{0, \mu_\nu |\xi_\nu|, \mu_\nu |2 - \xi_\nu|\}$
- Mixing angles are same as for quarks:

$$\sin\theta_{23}^l = \tfrac{1}{4} \left| \left(y_{11} + 2y_{22} + 2i\, y_{23} \right) (\varepsilon_l - \varepsilon_\nu) \right| \implies \text{small } \theta_{23}^l!$$

Majorana Neutrinos

Neutrinos must be (partially) Majorana in character!

<u>The Weinberg Operator:</u>

$$\mathcal{L} \supset \frac{1}{\Lambda} c_{ij}^{W} (L_i H)(L_j H)$$

<u>Two simplified cases:</u>

1. *"Type I Seesaw"* – $c^W = Y_\nu Y_\nu^T$, where

$$Y_\nu = \mu_\nu \left[i Y_3 + (1 - \xi_\nu) Y_3^2 + \varepsilon_\nu Y_5 + \delta_\nu \mathbb{I} \right]$$

2. *"Type II Seesaw"* – $c^W = \eta_{33} Y_3^2 + \eta_5 Y_5 + \eta_1 \mathbb{I}$

<u>PMNS Matrix:</u>

$$V_\nu \cdot c^W \cdot \left(c^W\right)^\dagger \cdot V_\nu{}^\dagger = \mathcal{P}^T \cdot \mathrm{diag}\left(y_{\nu 1}^2, y_{\nu 2}^2, y_{\nu 3}^2\right) \cdot \mathcal{P}; \quad \boxed{U_{\mathrm{PMNS}} = V_{lL} V_\nu^\dagger}$$

Numerical Results

arXiv: 1306.6879,
S. Antusch & V. Maurer

Observable	$\overline{MS}$ Value, $\mu = 1$ TeV
y_u	6.3×10^{-6}
y_c	3.104×10^{-3}
y_t	0.8685
y_d	1.364×10^{-5}
y_s	2.74×10^{-4}
y_b	1.388×10^{-2}
y_e	2.8482×10^{-6}
y_μ	6.0127×10^{-4}
y_τ	1.02213×10^{-2}
$\sin\theta^q_{12}$	0.2254
$\sin\theta^q_{13}$	3.770×10^{-3}
$\sin\theta^q_{23}$	4.363×10^{-2}
$\sin\delta^q_{CP}$	0.9349

These are the data that Flavorspin must explain!

How to probe?

arXiv:1611.01514; NuFIT 3.0 (2016) [www.nu-fit.org]

Observable	Normal Hierarchy ($\Delta\chi^2 = 0$)	Inverted Hierarchy ($\Delta\chi^2 = 0.83$)
Δm^2_{12}	7.50×10^{-5} eV^2	7.50×10^{-5} eV^2
Δm^2_{13}	$+2.524 \times 10^{-3}$ eV^2	-2.444×10^{-3} eV^2
$\sin^2\theta^l_{12}$	0.306	0.306
$\sin^2\theta^l_{13}$	0.02166	0.02179
$\sin^2\theta^l_{23}$	0.441	0.587
$\sin\delta^l_{CP}$	-0.988	-0.993

Up-type:

$$|\xi_u| \in [6 \times 10^{-3}, 8 \times 10^{-3}]$$
$$|\varepsilon_u| \in [1 \times 10^{-3}, 2 \times 10^{-3}]$$
$$|\delta_u| \in [1 \times 10^{-5}, 2 \times 10^{-5}]$$

Down-type:

$$|\xi_d| \in [0.035, 0.037]$$
$$|\varepsilon_d| \in [0.06, 0.07]$$
$$|\delta_d| \in [6 \times 10^{-4}, 7 \times 10^{-4}]$$

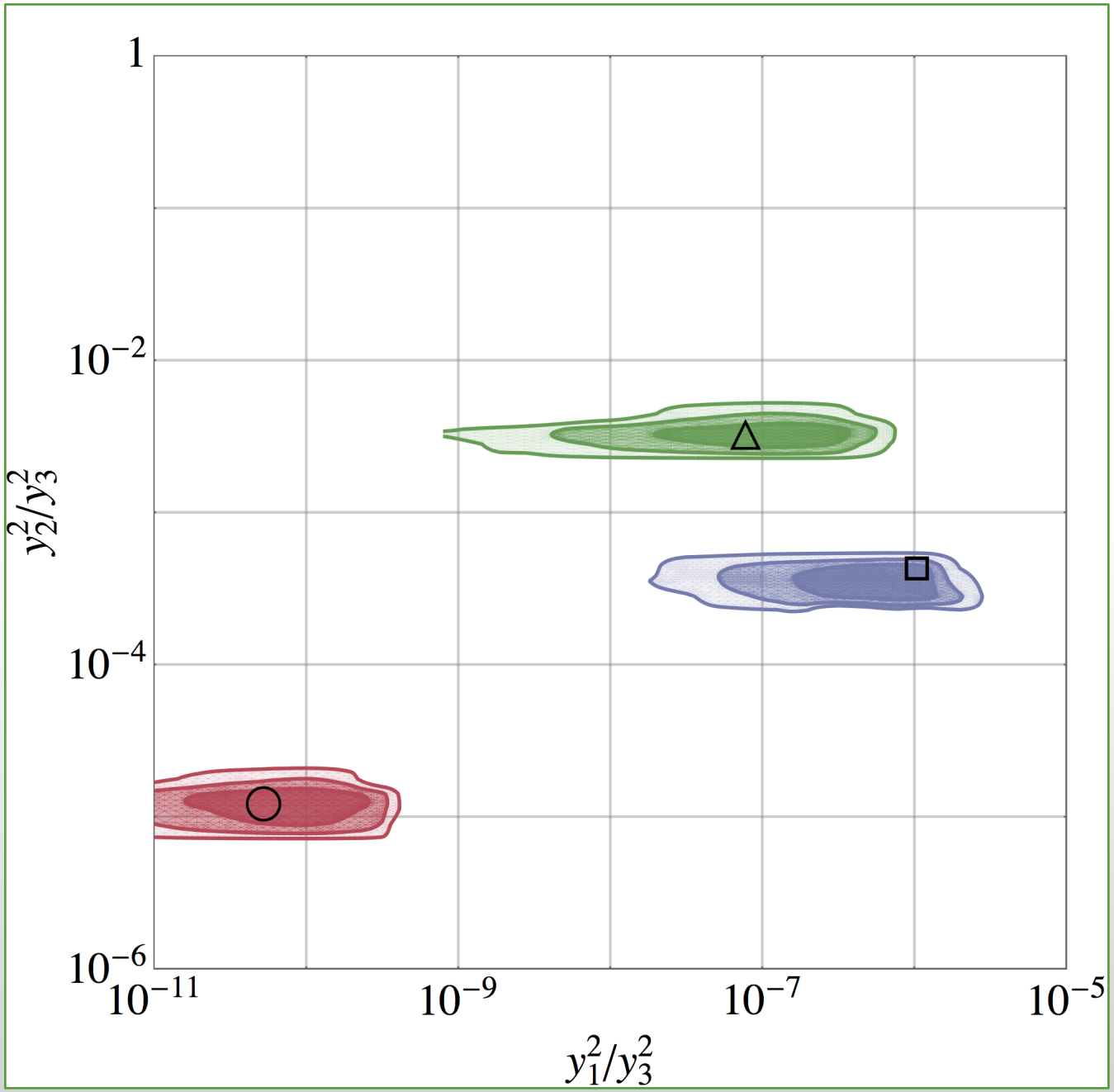
Electron-type:

$$|\xi_\ell| \in [0.11, 0.12]$$
$$|\varepsilon_\ell| \in [0.05, 0.06]$$
$$|\delta_\ell| \in [5 \times 10^{-4}, 6 \times 10^{-4}]$$

Elements of Y_5:

$$y_{11} \in [-0.01, 0.01],$$
$$y_{22} = 1,$$
$$y_{23} \in \pm[0.88, 0.92],$$

$$\Phi \equiv \sqrt{y_{12}^2 + y_{13}^2} \in [0.15, 0.16],$$
$$\varphi \equiv \arctan\left[\frac{y_{13}}{y_{12}}\right] \in [-\pi, \pi].$$



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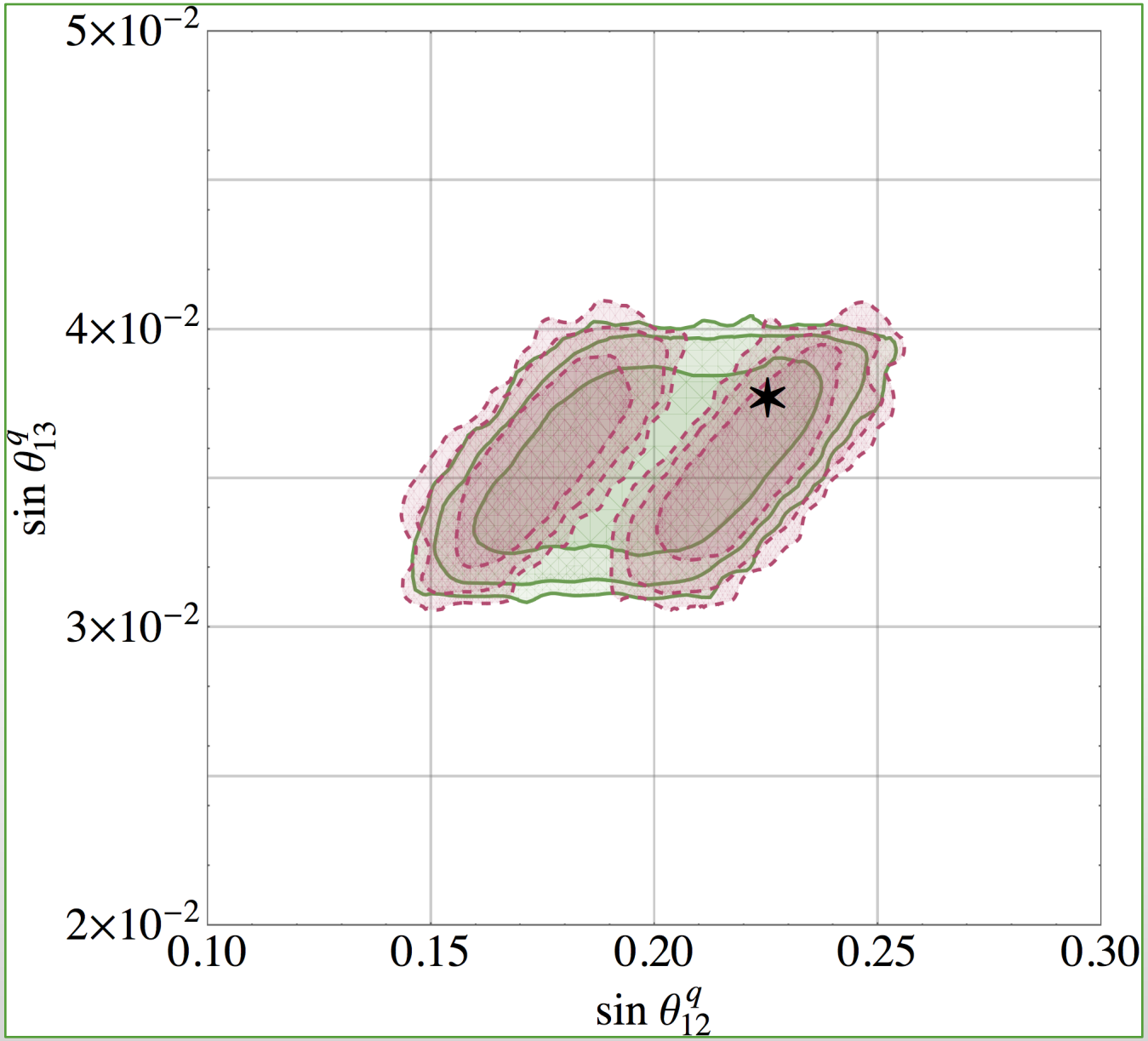

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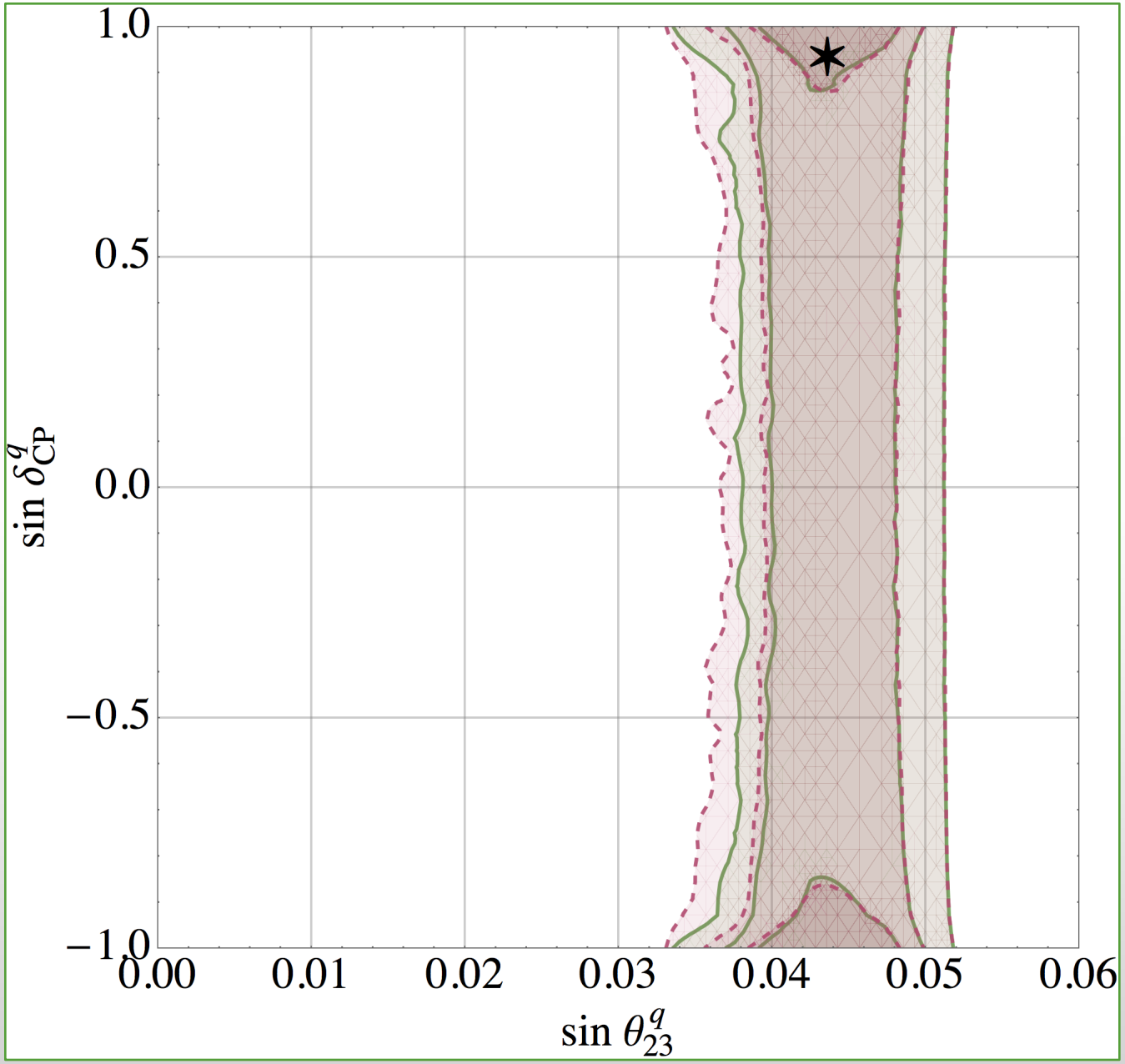
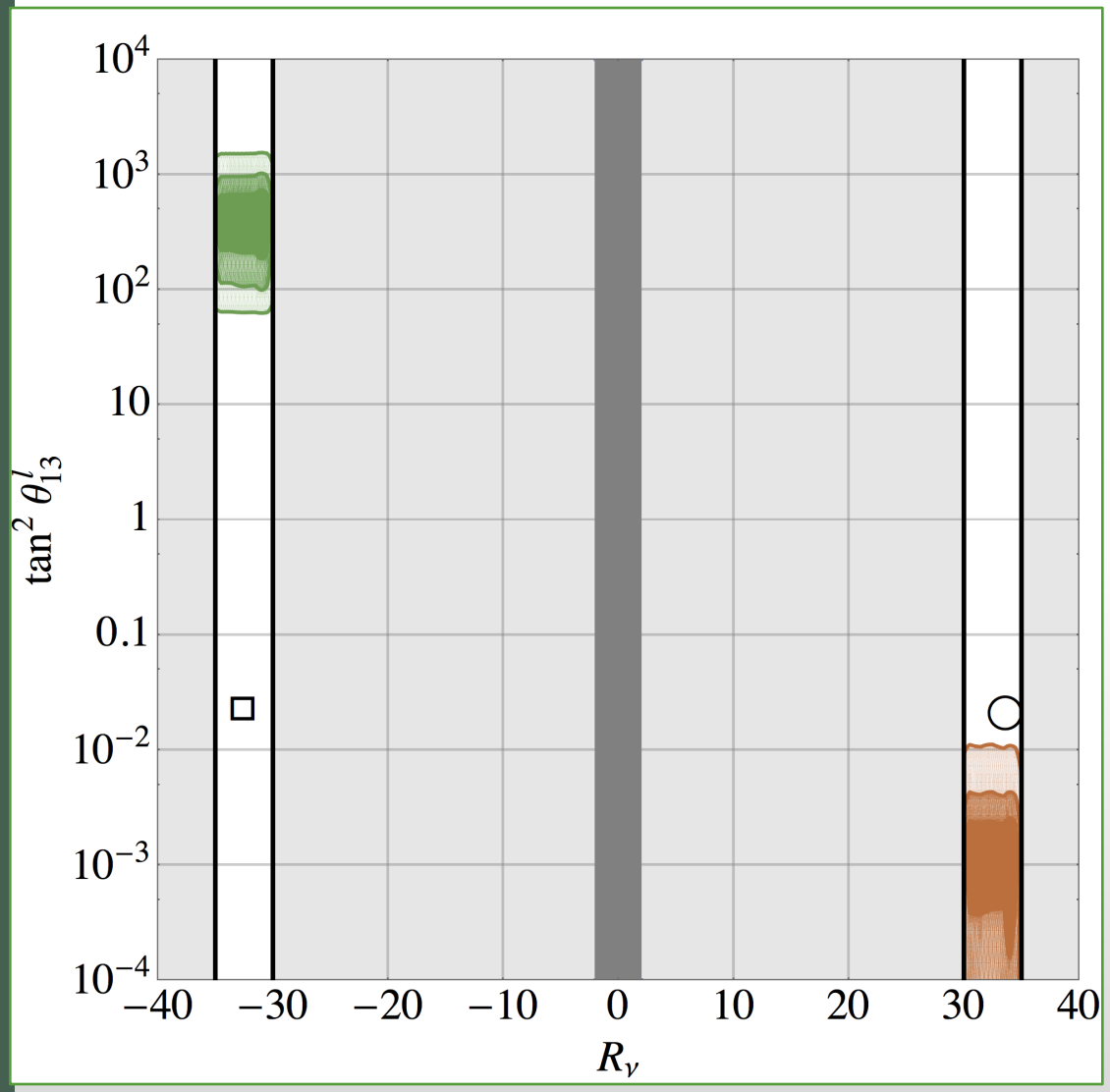
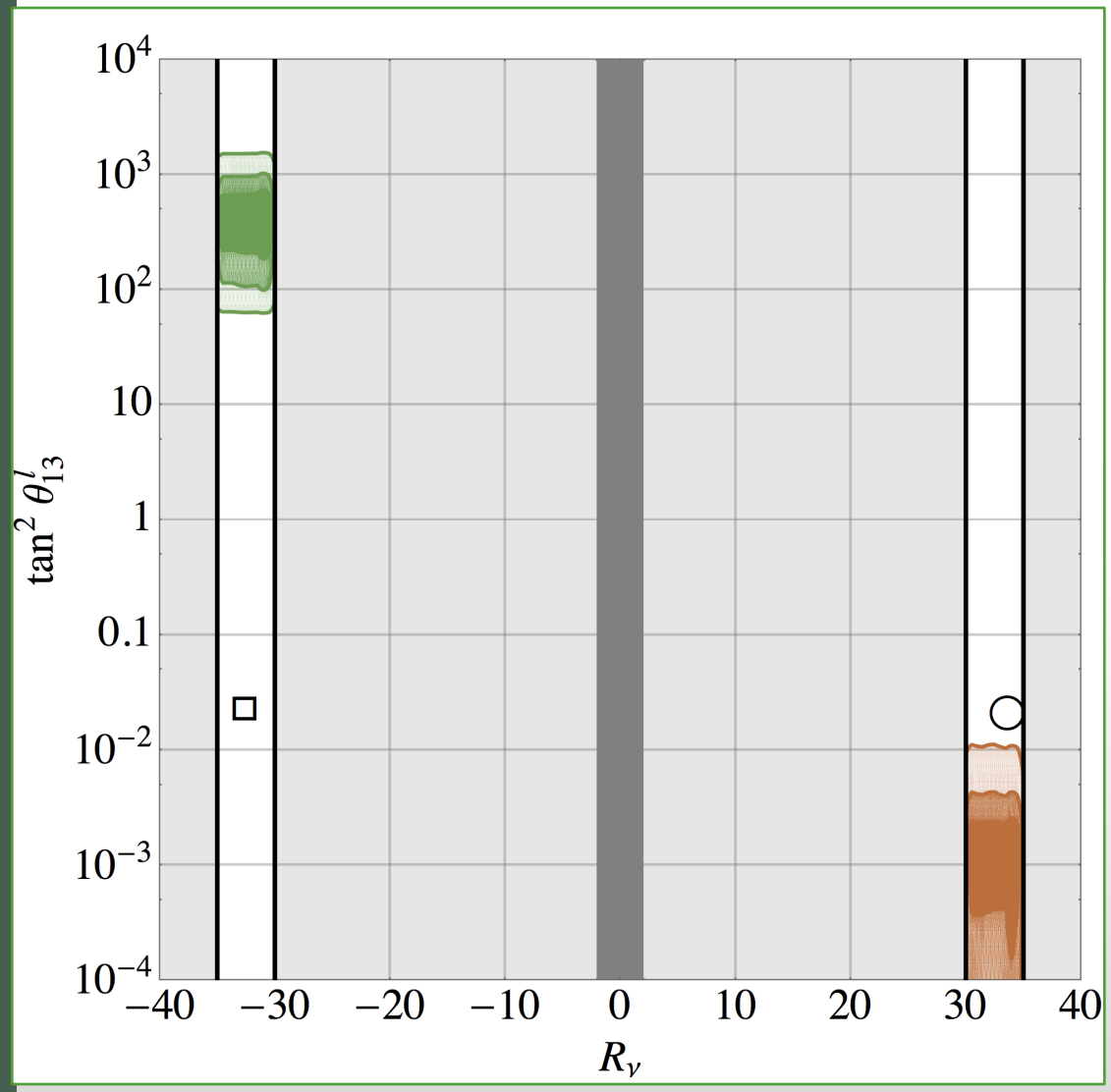
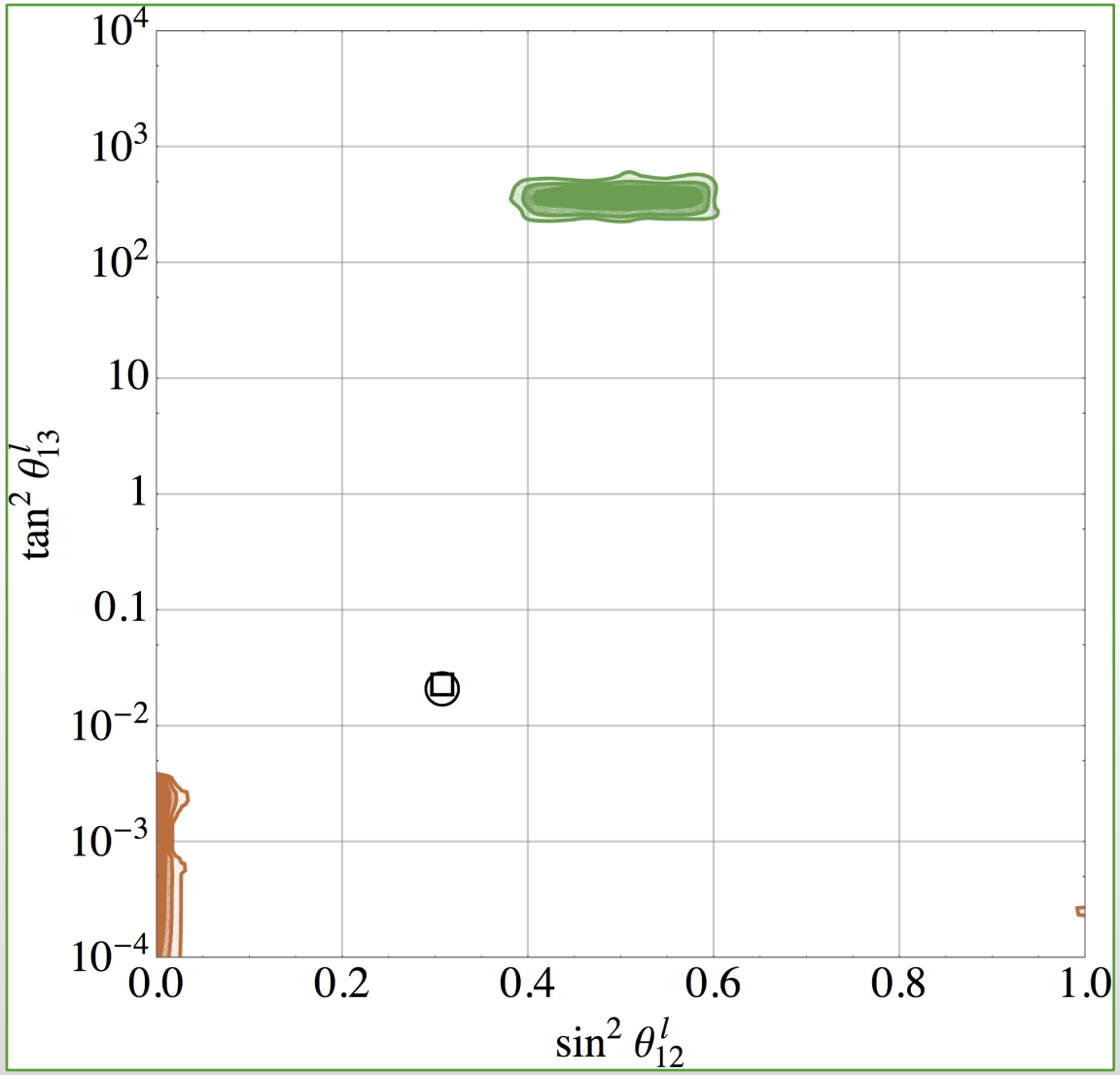




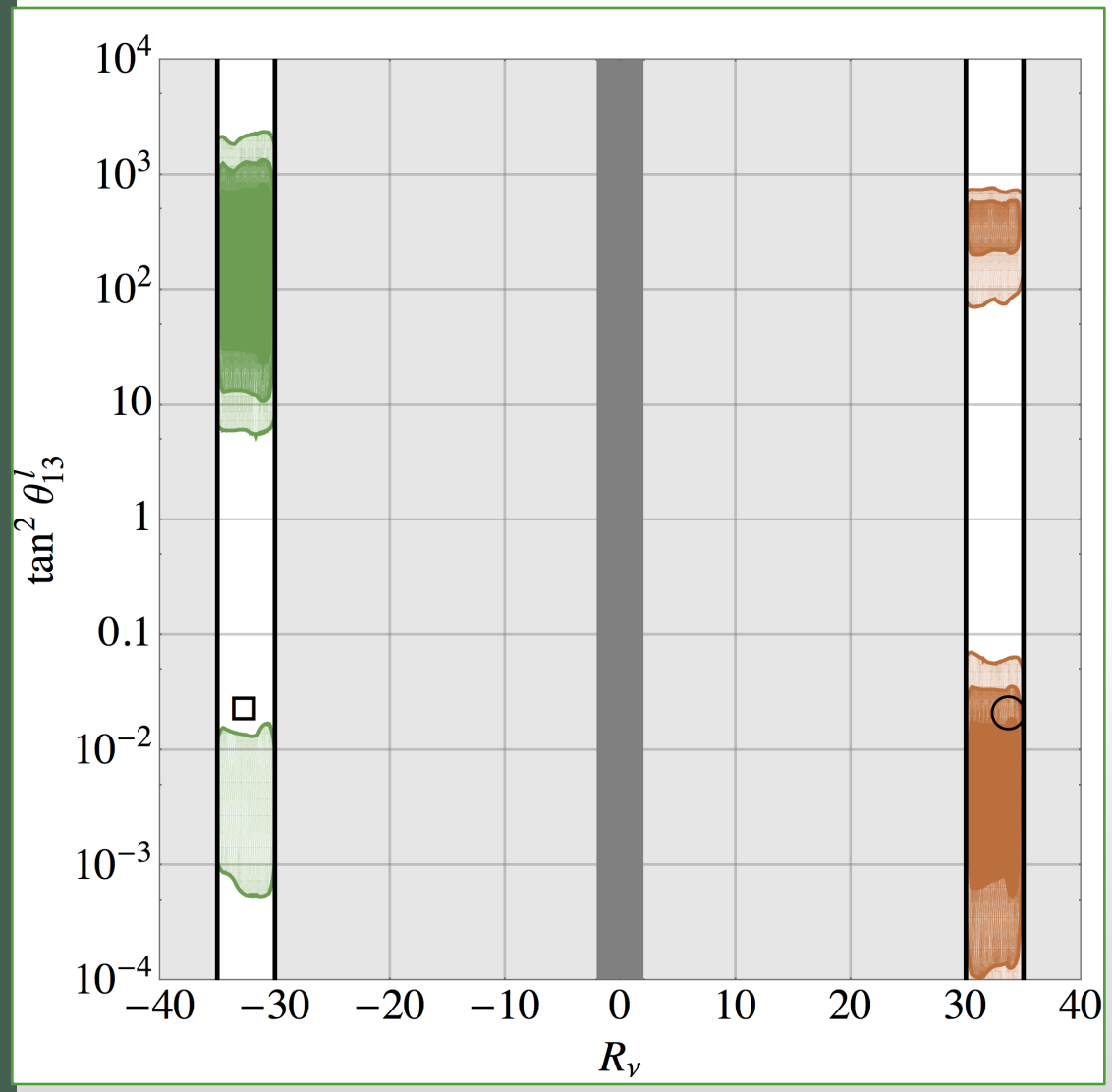
$$R_\nu = \begin{cases} \dfrac{m_3^2 - m_1^2}{m_2^2 - m_1^2}, & m_3^2 - m_2^2 > m_2^2 - m_1^2 \\[2ex] \dfrac{m_1^2 - m_2^2}{m_3^2 - m_2^2}, & m_3^2 - m_2^2 < m_2^2 - m_1^2 \end{cases}$$

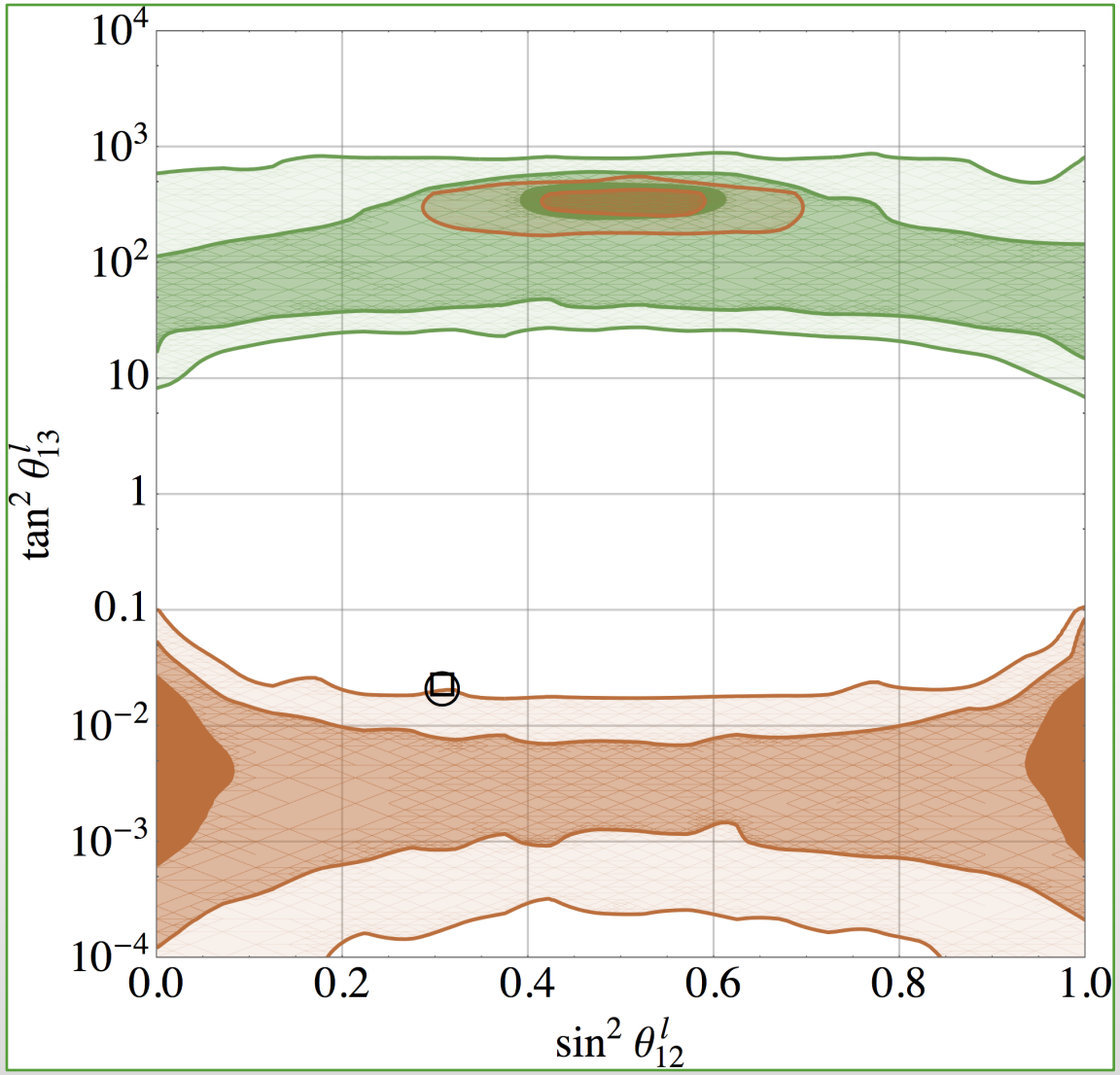
TYPE I SEESAW


10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
$\tan^2\theta^l_{13}$
−40
−30
−20
−10
0
10
20
30
40
R_ν


10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
$\tan^2\theta^l_{13}$
0.0
0.2
0.4
0.6
0.8
1.0
$\sin^2\theta^l_{12}$

TYPE I SESAW





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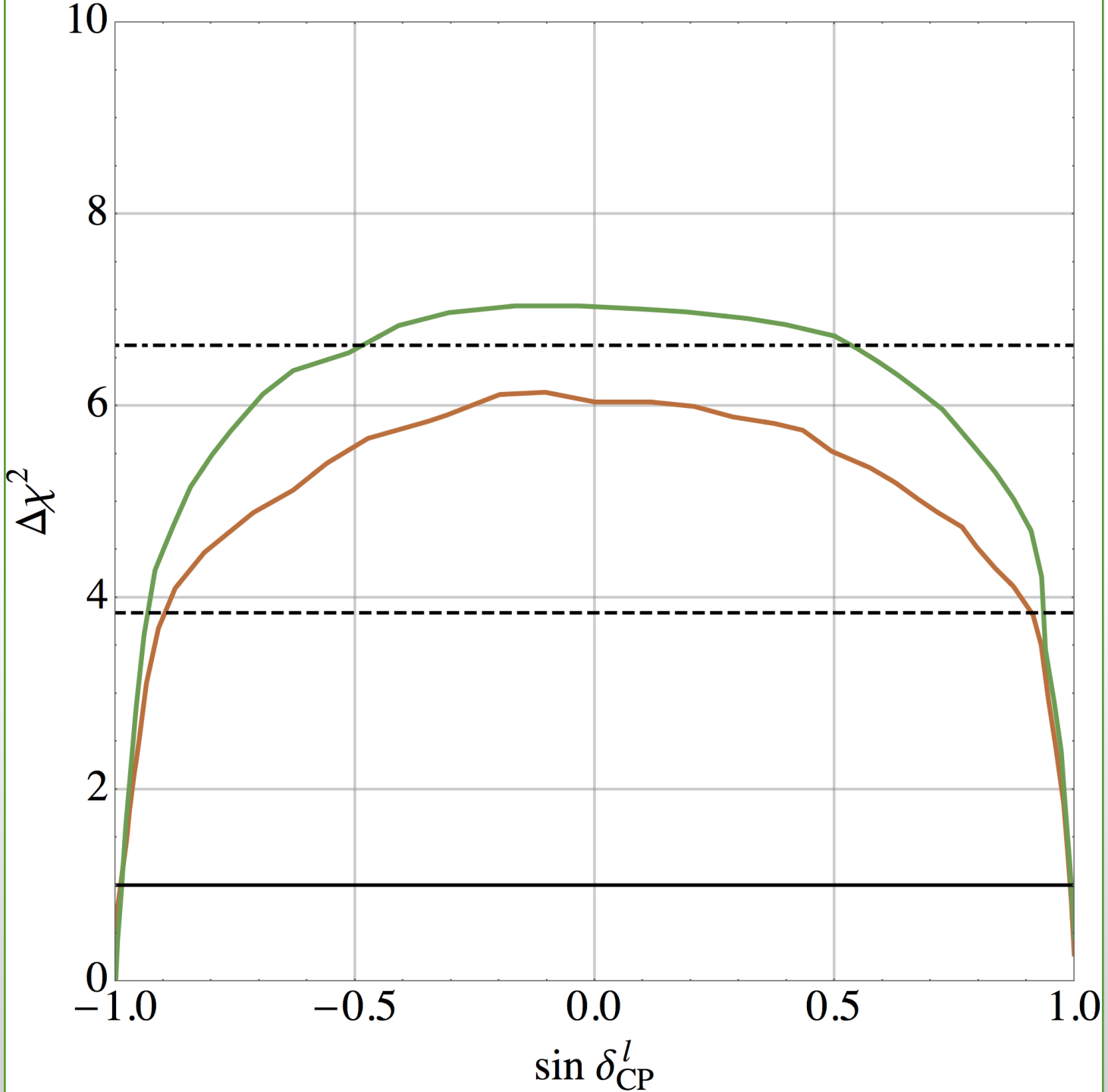

TYPE II SEESAW

Flavor-Changing Neutral Currents

<u>Higher-Dimensional Operators:</u> All non-trivial flavor structure comes from Y_3 and Y_5.

<u>Possible fermion bilinears:</u>

$$\mathcal{Q}_\alpha \sim c_{\alpha,ij} f_i \overline{f_j'}; \qquad c_{\alpha,ij} f_i f_j'; \qquad c_{\alpha,ij} \overline{f_i}\,\overline{f_j'}$$

$$f^{(\prime)} = u_{L,R}, d_{L,R}, e_{L,R}, \nu_L$$

<u>Flavor structure:</u>

$$c_\alpha = iY_3 + \left(1 - \xi_\alpha\right) Y_3^2 + \varepsilon_\alpha Y_5 + \delta_\alpha \mathbb{I}$$

Flavor-Changing Neutral Currents

<u>Three classes of bilinears:</u>

1. $Q_\alpha \sim \bar{f} c_\alpha f'$, $f^{(\prime)} = u_{L,R}, d_{L,R}, e_{L,R}$

- *Contribute to, e.g., $b \to s\gamma$, $\mu \to e\gamma$, $\mu \to eee$, …*
- *These are suppressed!*

e.g., $\overline{d_L} c_\alpha d_L \Longrightarrow$

$$V_d c_\alpha V_d^\dagger \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & \xi_\alpha & (1+i)(\varepsilon_d - \varepsilon_\alpha) \\ 0 & (1-i)(\varepsilon_d - \varepsilon_\alpha) & \xi_\alpha - 2 \end{pmatrix}$$

2. $Q_\alpha \sim f c_\alpha f', \bar{f} c_\alpha \bar{f'}$, $f^{(\prime)} = u_{L,R}, d_{L,R}, e_{L,R}, \nu_L$

- *Not suppressed!*
- *These bilinears necessarily violate B–L, even if the operator doesn't.*

Flavor-Changing Neutral Currents

3. $Q_\alpha \sim \bar{\nu} c_\alpha f, \bar{f} c_\alpha \nu, f^{(\prime)} = u_{L,R}, d_{L,R}, e_{L,R}, \nu_L$

- *Not suppressed – $V_\nu \neq V_{uL}$, etc.*
- *Not easily probed at experiments.*

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– *Not easily probed at experiments.*

<u>Phenomenological Consequences:</u>

- FCNCs and *B*–*L* symmetry?
- Potentially large neutrino nonstandard interactions (NSI)
- Correlations between lepton-number violating processes:

– *Neutrinoless double beta decay ($0\nu\beta\beta$); muon-to-positron conversion*

– *See, e.g., arXiv:1611.00032; J.B., A. de Gouvêa, K.J. Kelly, A. Kobach*

What Have We Done?

<u>What Flavorspin is *not*:</u>

- A complete model of flavor – this is coming (eventually…)
- Absent of hierarchies & small parameters
- Completely devoid of flavor-changing neutral currents

<u>What Flavorspin *is*:</u>

- A novel approach to the flavor puzzle, cf. MFV
- Indicative of higher symmetry – $U(1)_{B-L}$, $U(1)_{\mu-\tau}$, etc.
- Predictive and falsifiable – Dirac neutrinos; Type I seesaw