$\nu e \to \nu e$ SCATTERING WITH MASSIVE DIRAC AND MAJORANA NEUTRINOS AND GENERAL INTERACTIONS

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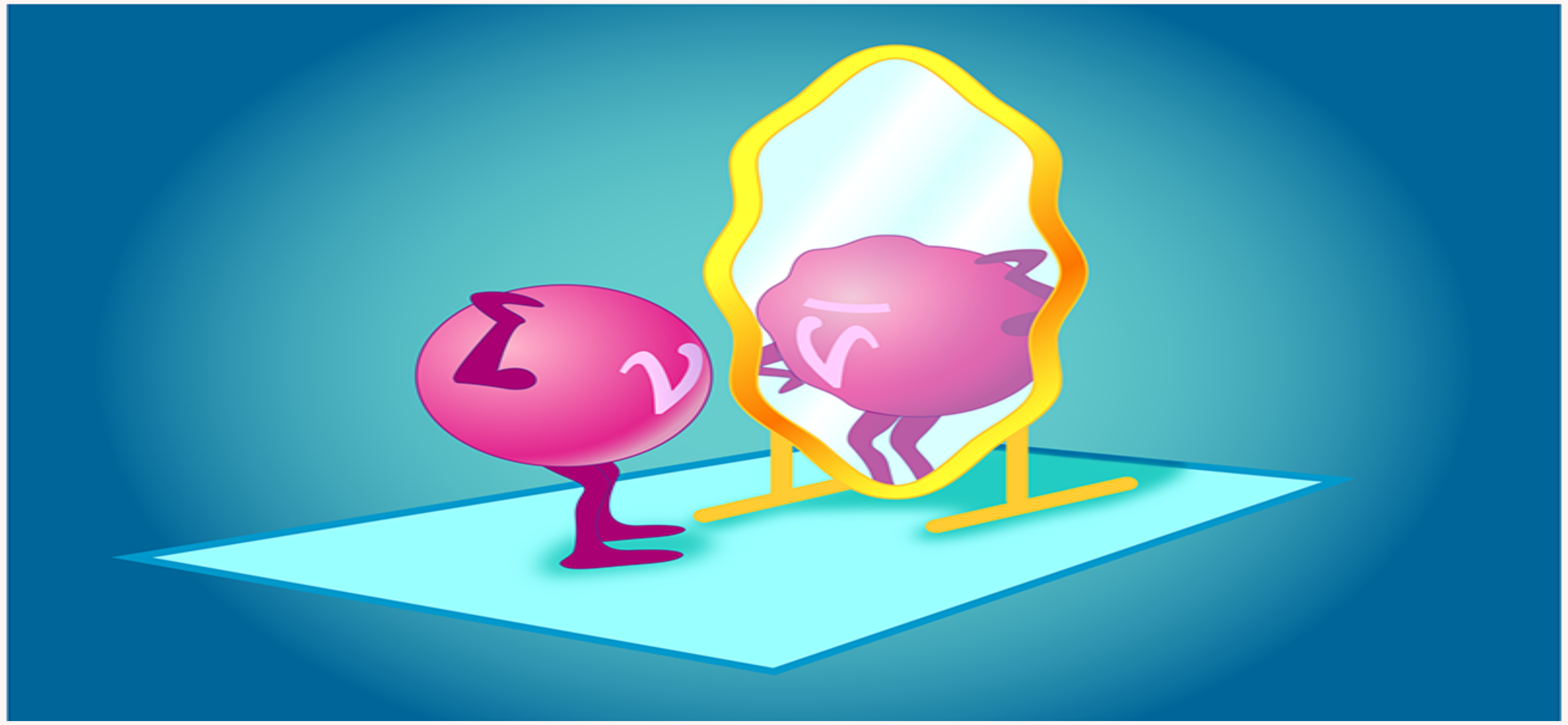
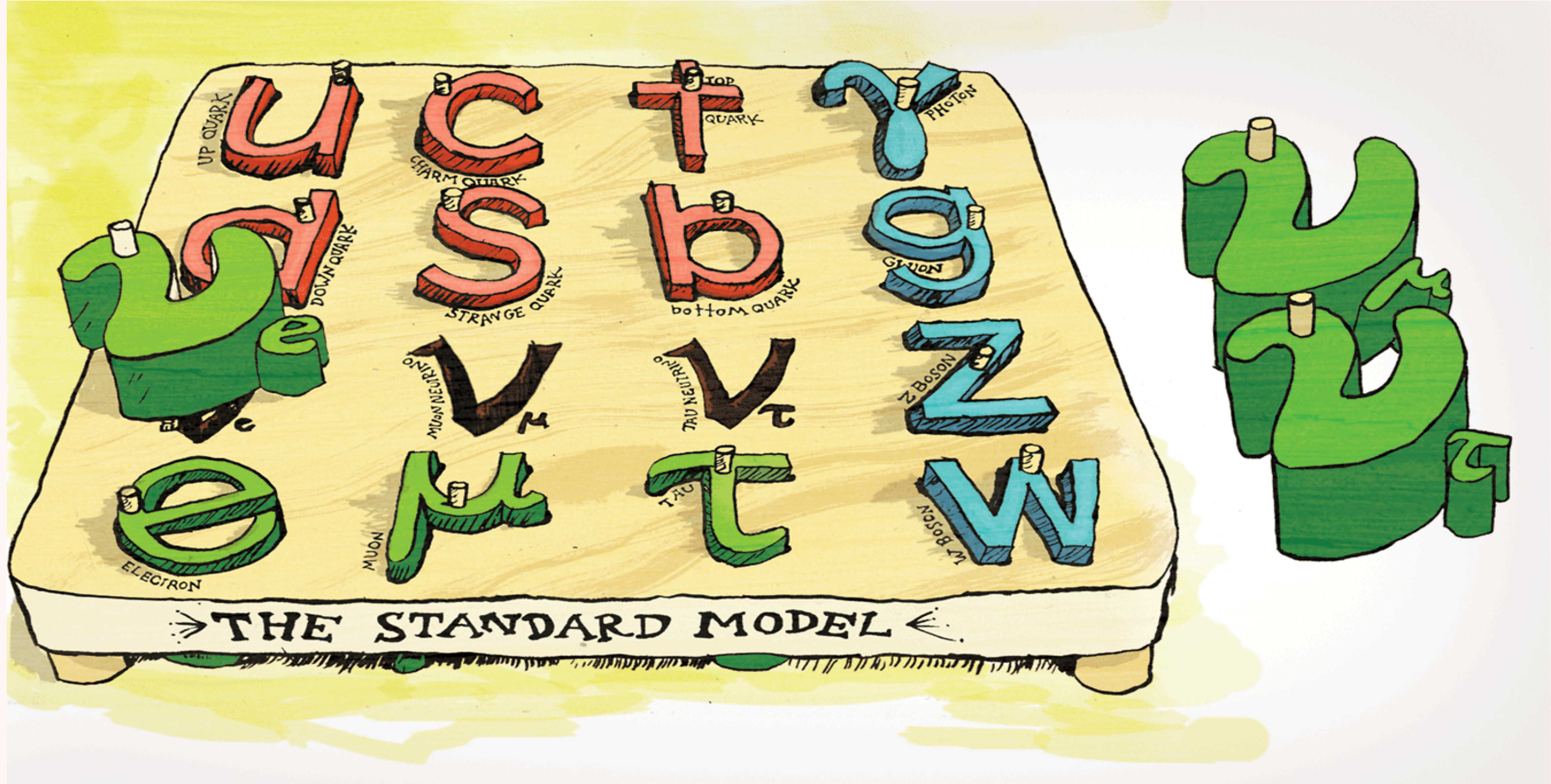
PRACTICAL DIRAC-MAJORANA CONFUSION THEOREM (DMCT)

- **The difference, in any observable, between Dirac and Majorana neutrinos in SM processes (SM gauge group + massive neutrinos) is proportional to some power of the neutrino mass $\left(\frac{m_\nu}{E}\right)^n$ (if neutrino variables are not measured).**

Boris Kayser, Phys.Rev.D 26 (1982) 1662





$$\mathrm{Re}(\mathscr{M}_{ij}(p_2, p_3)\mathscr{M}^*_{ji}(p_3, p_2)) \not\propto m_\nu^2 \, .$$

Alternatives

New Physics Effects

Measure Neutrino Variables

$$d\Gamma^M \propto \frac{1}{2}\sum_{i,j} |\,\mathscr{M}\,|^2 = \frac{1}{2}\,|\,\mathscr{M}(p_2, p_3)\,|^2 + \frac{1}{2}\,|\,\mathscr{M}(p_3, p_2)\,|^2 \to \Gamma^M \neq \Gamma^D$$

$\nu e \to \nu e$ Scattering

$$\mathscr{L} \supset \frac{G_F}{\sqrt{2}} \sum_{a=S,P,V,A,T} \bar{\nu}\Gamma^a \nu \left[\bar{l}\, \Gamma^a (C_a + \bar{D}_a i\gamma^5) l \right] + h.c.,$$

where Γ^a, with $a = S, P, V, A, T$.

$$D_a \equiv \bar{D}_a, \quad a = S, P, T,$$
$$D_a \equiv i\bar{D}_a, \quad a = V, A,$$

Majorana condition $\nu_j = \nu_j^c = C\bar{\nu}_j^T$ → $C_V = D_V = C_T = D_T = 0$

and

Double all other couplings

See also Rodejohan, Xu & Yaguna JHEP05(2017)024

The cross section of elastic scattering of neutrinos (antineutrinos) with massive charged leptons at energies where the local interaction approximation holds, neglecting neutrino masses, is

Incoming (anti) neutrinos are (right) left-handed

$$\frac{d\sigma}{dT}(\nu + \mathrm{e}) = \frac{G_F^2 M}{2\pi}\left[A + 2B\left(1 - \frac{T}{E_\nu}\right) + C\left(1 - \frac{T}{E_\nu}\right)^2 + D\frac{MT}{4E_\nu^2}\right],$$

$$\frac{d\sigma}{dT}(\bar{\nu} + \mathrm{e}) = \frac{G_F^2 M}{2\pi}\left[C + 2B\left(1 - \frac{T}{E_\nu}\right) + A\left(1 - \frac{T}{E_\nu}\right)^2 + D\frac{MT}{4E_\nu^2}\right],$$

$$A \equiv \frac{1}{4}(C_A - D_A + C_V - D_V)^2 + \frac{1}{8}(C_P^2 + C_S^2 + D_P^2 + D_S^2 + 8C_T^2 + 8D_T^2)$$
$$+\frac{1}{2}(C_P C_T - C_S C_T + D_P D_T - D_S D_T),$$
$$B \equiv -\frac{1}{8}(C_P^2 + C_S^2 + D_P^2 + D_S^2 - 8C_T^2 - 8D_T^2),$$
$$C \equiv \frac{1}{4}(C_A + D_A - C_V - D_V)^2 + \frac{1}{8}(C_P^2 + C_S^2 + D_P^2 + D_S^2 + 8C_T^2 + 8D_T^2)$$
$$-\frac{1}{2}(C_P C_T - C_S C_T + D_P D_T - D_S D_T),$$
$$D \equiv (C_A - D_V)^2 - (C_V - D_A)^2 - 4(C_T^2 + D_T^2) + C_S^2 + D_P^2.$$

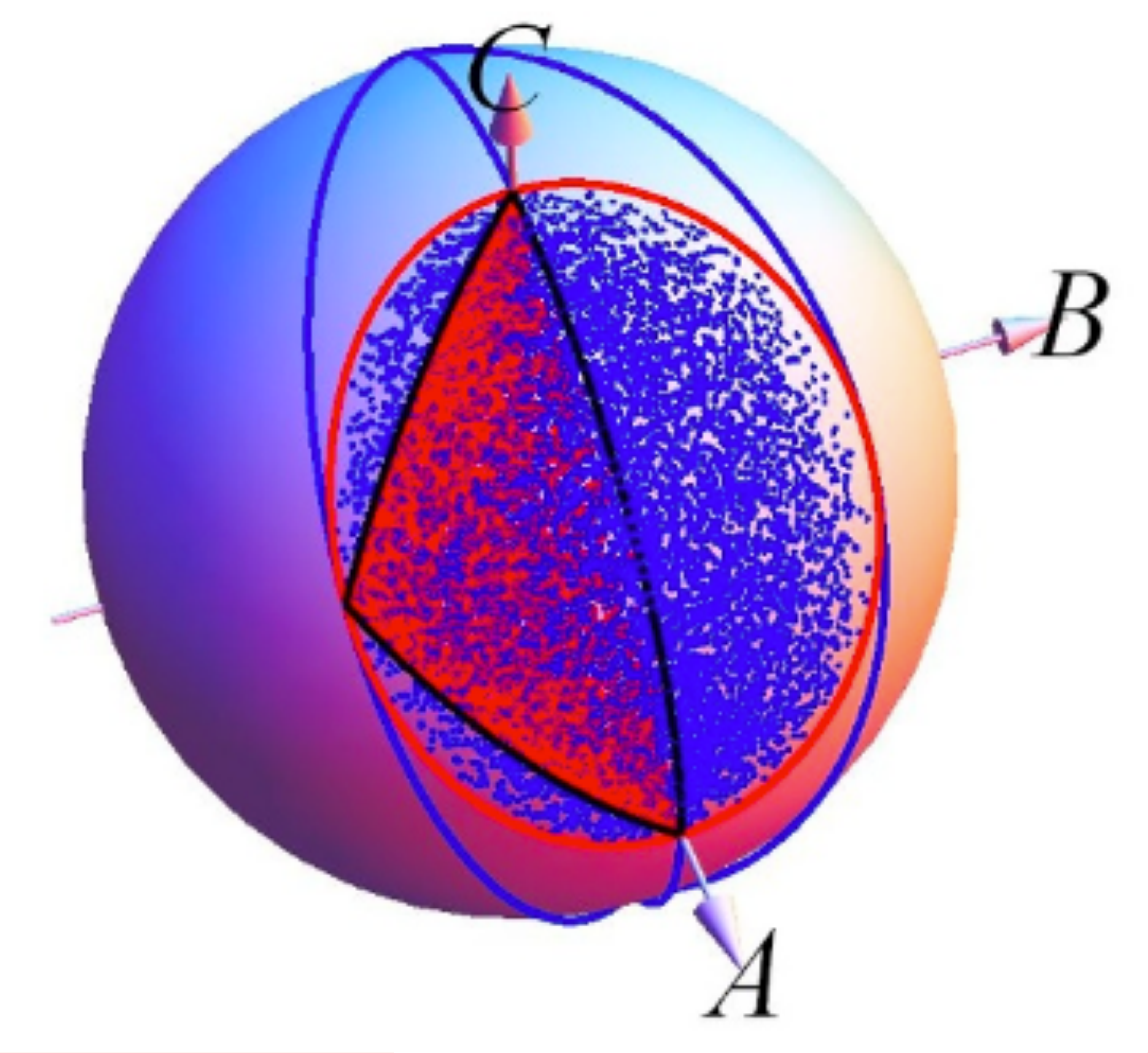
where E_ν is the incident neutrino energy, T and M are the recoil energy and mass of the charged lepton, respectively.

Dirac vs Majorana (Rosen 1982)

$$R_\rho \equiv \frac{2(A + 2B + C)}{A + C}$$

$$0 \leq R_\rho \leq 4 \quad (Dirac)$$
$$0 \leq R_\rho \leq 2 \quad (Majorana)$$

In the SM: $R_\rho = 2$



Rodejohan, Xu & Yaguna JHEP05(2017)024

Cross section considering neutrino masses

$$\nu_{lL} = \sum_j U_{lj} N_{jL}, \quad \nu'_{lR} = \sum_j V_{lj} N_{jR},$$

$$\frac{d\sigma}{dT}(\nu + \mathrm{e}) = \sum_{i,f} |U_{\ell i}|^2 \frac{G_F^2 M}{2\pi} \frac{E_\nu^2}{E_\nu^2 - m_{\nu_i}^2} \left\{ A + 2B\left(1 - \frac{T}{E_\nu}\right) + C\left(1 - \frac{T}{E_\nu}\right)^2 \right.$$
$$+ D\frac{MT}{4E_\nu^2} + \frac{(m_{\nu_i}^2 - m_{\nu_f}^2)}{2ME_\nu}\left[(A + 2B) + C\left(1 - \frac{T}{E_\nu}\right) + F\frac{m_{\nu_f}}{E_\nu}\right]$$
$$\left. - B\frac{m_{\nu_i}^2 T}{ME_\nu^2} + \frac{m_{\nu_f}}{E_\nu}\left[G + F\left(1 - \frac{T}{E_\nu}\right)\right] + D\frac{m_{\nu_i}^2 + m_{\nu_f}^2}{8E_\nu^2} \right\},$$

$$\frac{d\sigma}{dT}(\bar{\nu} + \mathrm{e}) = \sum_{i,f} |U_{\ell i}|^2 \frac{G_F^2 M}{2\pi} \frac{E_\nu^2}{E_\nu^2 - m_{\nu_i}^2} \left\{ C + 2B\left(1 - \frac{T}{E_\nu}\right) + A\left(1 - \frac{T}{E_\nu}\right)^2 \right.$$
$$+ D\frac{MT}{4E_\nu^2} + \frac{(m_{\nu_i}^2 - m_{\nu_f}^2)}{2ME_\nu}\left[(C + 2B) + A\left(1 - \frac{T}{E_\nu}\right) - G\frac{m_{\nu_f}}{E_\nu}\right]$$
$$\left. - B\frac{m_{\nu_i}^2 T}{ME_\nu^2} - \frac{m_{\nu_f}}{E_\nu}\left[F + G\left(1 - \frac{T}{E_\nu}\right)\right] + D\frac{m_{\nu_i}^2 + m_{\nu_f}^2}{8E_\nu^2} \right\},$$

$$A \equiv |U_{\ell f}|^2 \left[\frac{1}{4}(C_A - D_A + C_V - D_V)^2\right] + |V_{\ell f}|^2 \left[\frac{1}{8}(C_P^2 + C_S^2 + D_P^2 + D_S^2 + 8C_T^2 + 8D_T^2) + \frac{1}{2}(C_P C_T - C_S C_T + D_P D_T - D_S D_T)\right],$$

$$B \equiv -|V_{\ell f}|^2 \left[\frac{1}{8}(C_P^2 + C_S^2 + D_P^2 + D_S^2 - 8C_T^2 - 8D_T^2)\right],$$

$$C \equiv |U_{\ell f}|^2 \left[\frac{1}{4}(C_A + D_A - C_V - D_V)^2\right] + |V_{\ell f}|^2 \left[\frac{1}{8}(C_P^2 + C_S^2 + D_P^2 + D_S^2 + 8C_T^2 + 8D_T^2) - \frac{1}{2}(C_P C_T - C_S C_T + D_P D_T - D_S D_T)\right],$$

$$D \equiv |U_{\ell f}|^2 \left[(C_A - D_V)^2 - (C_V - D_A)^2\right] + |V_{\ell f}|^2 \left[-4(C_T^2 + D_T^2) + C_S^2 + D_P^2\right],$$

$$F \equiv \mathrm{Re}\left[U_{\ell f} V_{\ell f}^*\right] \frac{1}{4}[(C_S + 6C_T)(C_V - D_A) + (C_P - 6C_T)(C_A - D_V)],$$

$$G \equiv \mathrm{Re}\left[U_{\ell f} V_{\ell f}^*\right] \frac{1}{4}[(C_S - 6C_T)(C_V - D_A) - (C_P + 6C_T)(C_A - D_V)].$$

Possible neutrino mass effects

Neutrino flavor	m_{ν_f} (MeV)	$\lvert U_{\ell 4}\rvert^2$	Linear term suppression $\lvert U_{\ell 4}\rvert^2 m_{\nu_f}/E_\nu$		Quadratic term suppression $\lvert U_{\ell 4}\rvert^2 m_{\nu_f}^2/E_\nu^2$	
			E_ν 500 MeV	E_ν 2500 MeV	E_ν 500 MeV	E_ν 2500 MeV
$l = e$ [36]	150-375	10^{-8}	10^{-9}	10^{-10}-10^{-9}	10^{-10}-10^{-9}	10^{-10}
	375-440	10^{-9}	10^{-10}	10^{-10}	10^{-10}	10^{-11}
$l = \mu$ [37]	10	10^{-3}	10^{-5}	10^{-6}	10^{-7}	10^{-8}
	20	10^{-4}	10^{-6}	10^{-7}	10^{-7}	10^{-9}
	50	10^{-5}	10^{-6}	10^{-7}	10^{-7}	10^{-9}
	100	10^{-6}	10^{-7}	10^{-8}	10^{-8}	10^{-9}
$l = \tau$ [38]	100-200	10^{-3}	10^{-4}	10^{-4}	10^{-4}	10^{-5}
	300-400	10^{-4}	10^{-4}	10^{-5}	10^{-4}	10^{-6}-10^{-5}
	500-800	10^{-5}	10^{-5}	10^{-6}	10^{-5}	10^{-6}
	900-1100	10^{-5}	10^{-5}	10^{-6}	10^{-5}	10^{-6}

E. Cortina Gil et al.
Phys. Lett. B, vol. 778, pp. 137–145, 2018

P. Abratenko et al. arXiv: 2310.
07660 [hep-ex].

R. Barouki, G. Marocco, and S. Sarkar,
SciPost Phys., vol. 13, p. 118, 2022.

SM case

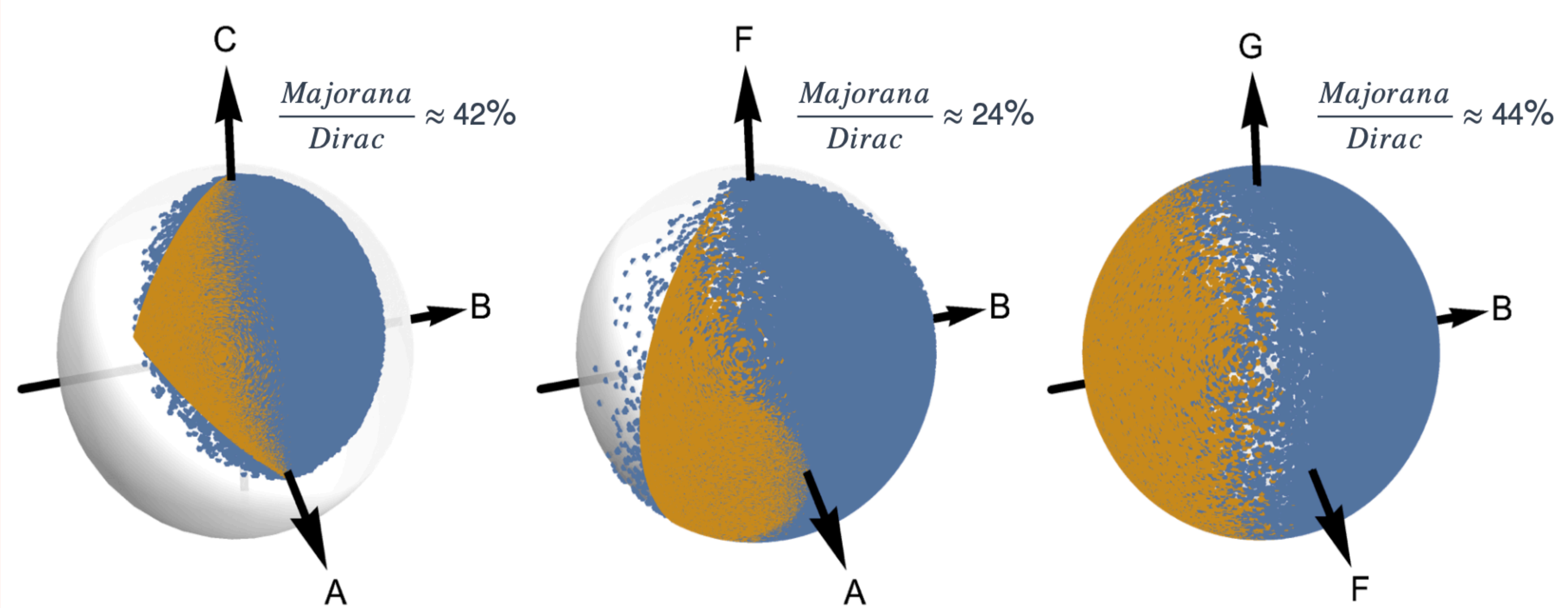
$$
\text{Dirac}\begin{cases}
C_V^{\text{SM}}=2g_V^\nu g_V^l, & D_V^{\text{SM}}=-2g_V^\nu g_A^l,\\
C_A^{\text{SM}}=2g_A^\nu g_A^l, & D_A^{\text{SM}}=-2g_A^\nu g_V^l,\\
C_S^{\text{SM}}=0, & D_S^{\text{SM}}=0,\\
C_P^{\text{SM}}=0, & D_P^{\text{SM}}=0,\\
C_T^{\text{SM}}=0, & D_T^{\text{SM}}=0,
\end{cases}
\quad
\text{Majorana}\begin{cases}
C_V^{\text{SM}}=0, & D_V^{\text{SM}}=0,\\
C_A^{\text{SM}}=4g_A^\nu g_A^l, & D_A^{\text{SM}}=-4g_A^\nu g_V^l,\\
C_S^{\text{SM}}=0, & D_S^{\text{SM}}=0,\\
C_P^{\text{SM}}=0, & D_P^{\text{SM}}=0,\\
C_T^{\text{SM}}=0, & D_T^{\text{SM}}=0.
\end{cases}
$$

$$
g_V^\nu=g_A^\nu=\frac{1}{2},\quad g_V^l=-\frac{1}{2}+2s_{\text{w}}^2,\quad g_A^l=-\frac{1}{2}\,.
$$

Parameter	Dirac and Majorana
A	$\lvert U_{\ell f}\rvert^2(1-2s_{\text{w}}^2)^2$
B	0
C	$\lvert U_{\ell f}\rvert^2 4s_{\text{w}}^4$
D	$\lvert U_{\ell f}\rvert^2\left(1-(1-4s_{\text{w}}^2)^2\right)$
F	0
G	0

SM case + C_T

Parameter	Dirac	Majorana
A	$\lvert U_{\ell f}\rvert^2(1-2s_{\rm w}^2)^2+\lvert V_{\ell f}\rvert^2 C_T^2$	$\lvert U_{\ell f}\rvert^2(1-2s_{\rm w}^2)^2$
B	$\lvert V_{\ell f}\rvert^2 C_T^2$	0
C	$\lvert U_{\ell f}\rvert^2 4s_{\rm w}^4+\lvert V_{\ell f}\rvert^2 C_T^2$	$\lvert U_{\ell f}\rvert^2 4s_{\rm w}^4$
D	$\lvert U_{\ell f}\rvert^2\left(1-(1-4s_{\rm w}^2)^2\right)-4\lvert V_{\ell f}\rvert^2 C_T^2$	$\lvert U_{\ell f}\rvert^2\left(1-(1-4s_{\rm w}^2)^2\right)$
F	$6\,\mathrm{Re}\left[U_{\ell f}V_{\ell f}^*\right] C_T\ s_{\rm w}^2$	0
G	$3\,\mathrm{Re}\left[U_{\ell f}V_{\ell f}^*\right] C_T(1-2s_{\rm w}^2)$	0

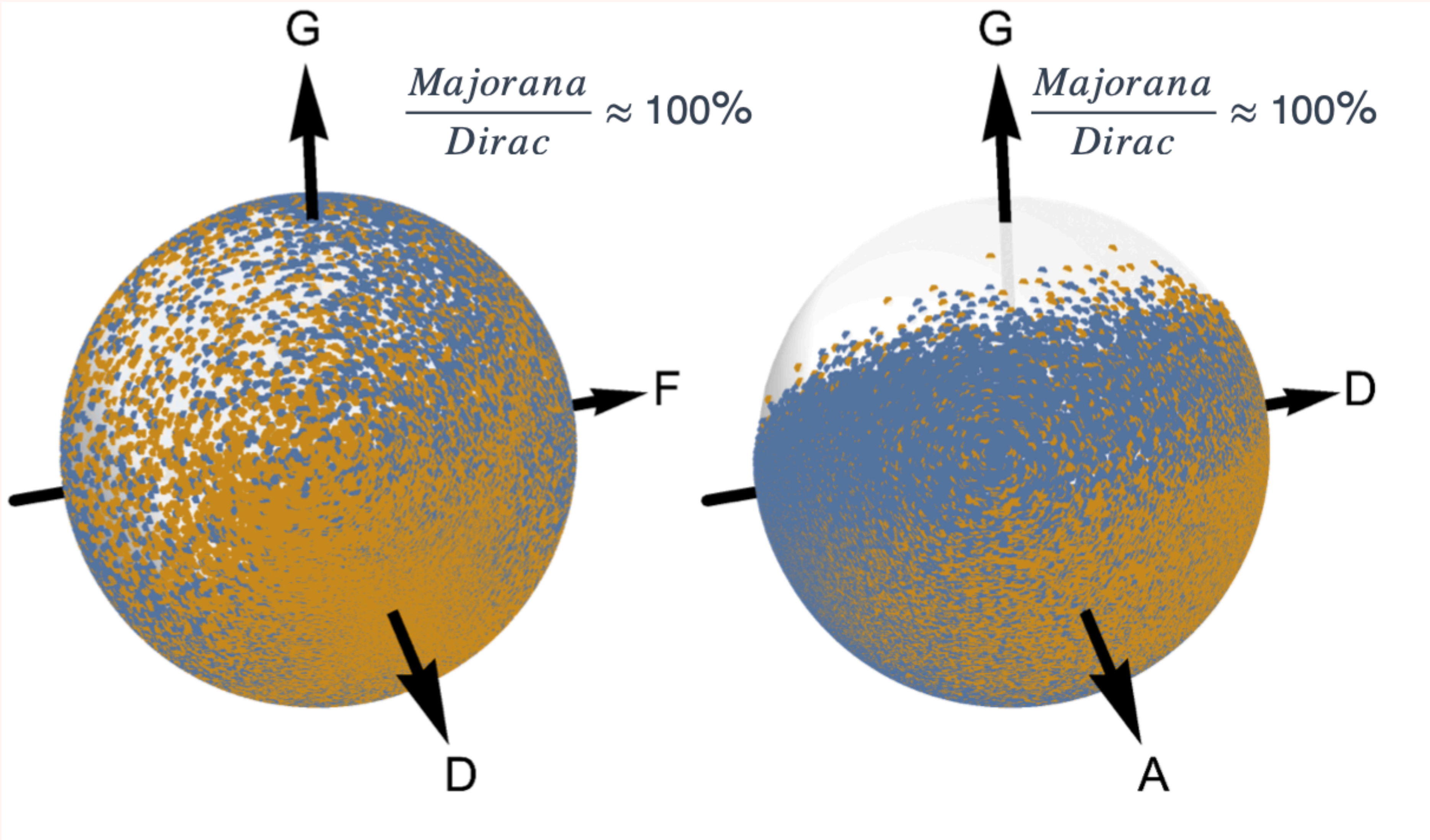


DIRAC

MAJORANA

$$B = -\frac{1}{8}(C_P^2 + C_S^2 + D_P^2 + D_S^2) + C_T^2 + D_T^2 \quad \textbf{(Dirac)},$$

$$B = -\frac{1}{8}(C_P^2 + C_S^2 + D_P^2 + D_S^2) \quad \textbf{(Majorana)},$$



What is new

- We have calculated the neutrino-electron elastic scattering cross section in the presence of general new interactions including all the effects due to finite neutrino masses, generalizing the previous results

- We have introduced two new parameters that arise due to considering finite neutrino masses and studied the effects of a possible heavy neutrino sector with a non-negligible mixing, as well as the impact of the specific neutrino nature on the differential cross section.

- Specifically, for the case of a tau neutrino dispersion with a mass around 100-400 MeV and an incident neutrino energy on the ballpark of $10^2 - 10^3$ MeV, the linear term suppression could be of order $10^{-4} - 10^{-5}$, which is a shared feature with the quadratic neutrino-mass term, unlike the results obtained on analogous processes where its suppression was very large.

- Polarization effects can also be taken into account (A. Błaut and W. Sobków, Eur. Phys. J. C, vol. 80, no. 3, p. 261, 2020.)

Thank You!

BACKUP

NP COUPLINGS CONSTRAINTS

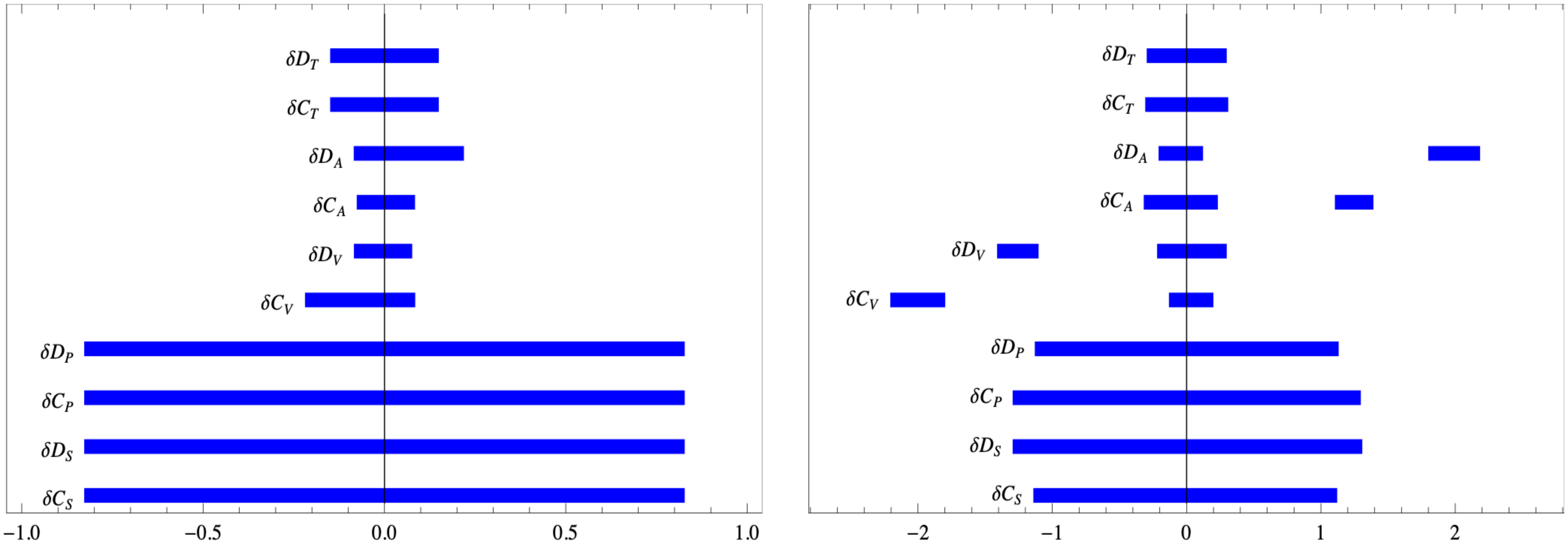


Figure 7. Constraints on $\delta C_a \equiv C_a - C_a^{\rm SM}$ and $\delta D_a \equiv D_a - D_a^{\rm SM}$ from one-parameter fitting of CHARM-II (left panel) and TEXONO (right panel). Blue bars represent 90% C.L. allowed values for δC_a and δD_a. There are two local minima for $C_{A,V}$ and $D_{A,V}$ in the fit of TEXONO. The slightly more minimal global minimum is around -2 for C_V, 0 for D_V, 0 for C_A and $+2$ for D_A. In the SM, $C_{V,A}$ and $D_{V,A}$ are non-zero for Dirac neutrinos, while only C_A and D_A are non-zero for Majorana neutrinos. The plot assumes Dirac neutrinos.