The Theoretical Perspective on Future Neutrino Experiments

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New Tools for the Next Generation of
Particle Physics and Cosmology

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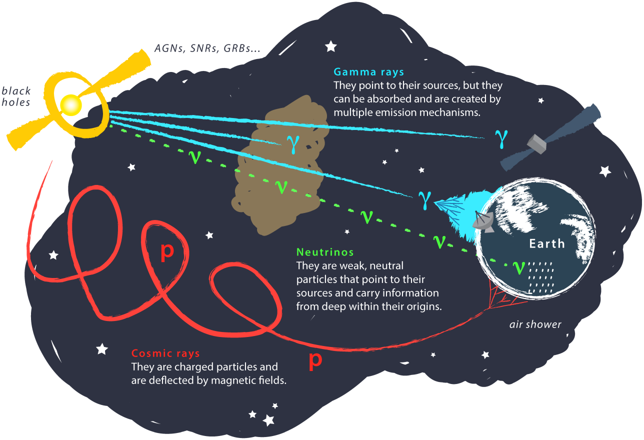
- There is a wind of crisis in traditional Particle Physics (mitigated by the flourishing of Astroparticle Physics and Cosmology).
- The discovery of the Higgs boson in 2012 at LHC was the triumph of the Standard Model of Glashow, Weinberg and Salam.
- After this peak of success now we live in an era in which the Standard Model is both a blessing and a curse:
  - Blessing: it is a consistent Quantum Field Theory that allows to compute with high precision all the known interactions of the known elementary particles.
  - Curse: its perfect working is hiding the way of further understanding of the fundamental properties of nature.
- Neutrinos can be powerful messengers of the physics beyond the SM.

Open problems that require New Physics

- From experiment:
  - Neutrino masses.
  - Dark Matter (keV sterile neutrino is a candidate).
  - Dark Energy (connection with the neutrino mass scale?).
  - Matter-antimatter asymmetry in the Universe (neutrino-induced leptogenesis).
- From theory:
  - Too many free numerical parameters ($19 + 7$ neutrino masses and mixing).
  - Why neutrino masses are so small? (seesaw Majorana neutrino masses?)
  - Why neutrino mixing is so different from quark mixing? (due to Majorana neutrino masses?)
  - Hierarchy problem (why the electroweak scale is so much smaller than the Planck scale?).
  - The strong CP problem.
  - Accidental conservation of $B - L$ global symmetry (broken by Majorana neutrino masses?).

The Power of Neutrinos

- Neutrinos are neutral and the weakest-interacting known particles.



Gamma rays
They point to their sources, but they can be absorbed and are created by multiple emission mechanisms.

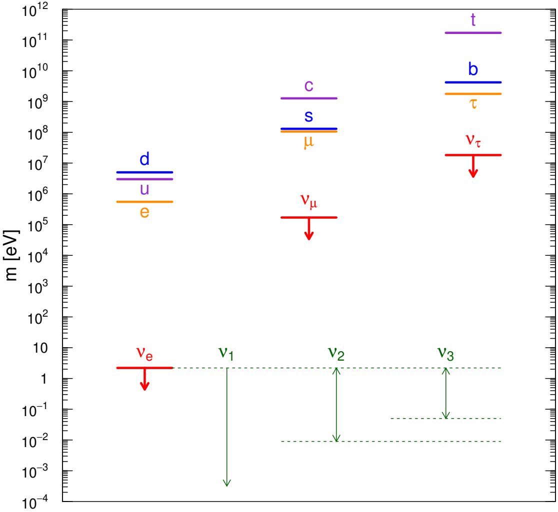
Neutrinos
They are weak, neutral particles that point to their sources and carry information from deep within their origins.

Cosmic rays
They are charged particles and are deflected by magnetic fields.

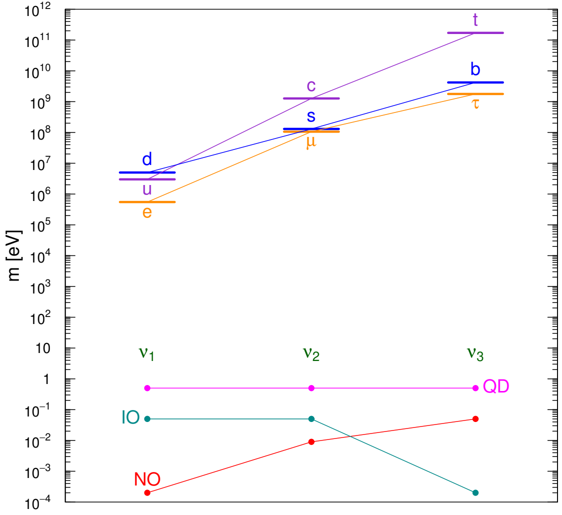
- Fantastic astrophysical messenger in the arising multimessenger era.

- Sensitive to very weak new interactions beyond the Standard Model:
  - New non-standard interactions.
  - Electromagnetic interactions (magnetic moments and charges).

- Neutrinos are the lightest known elementary particles with a huge gap in the mass scale of about 6-7 orders of magnitude.



Quasi-Degenerate →
Inverted Ordering→
Normal Ordering→



- The neutrino mass ordering is a model selector.
- The small neutrino masses can be Majorana masses beyond the Standard Model that break Lepton number conservation (L and $B - L$).

Origin of Neutrino Masses

	1st Generation	2nd Generation	3rd Generation
Quarks:	$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{matrix} u_R \\ d_R \end{matrix}$	$\begin{pmatrix} c_L \\ s_L \end{pmatrix} \quad \begin{matrix} c_R \\ s_R \end{matrix}$	$\begin{pmatrix} t_L \\ b_L \end{pmatrix} \quad \begin{matrix} t_R \\ b_R \end{matrix}$
Leptons:	$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} \quad \begin{matrix} \boxed{\nu_{eR}} \\ e_R \end{matrix}$	$\begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix} \quad \begin{matrix} \boxed{\nu_{\mu R}} \\ \mu_R \end{matrix}$	$\begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix} \quad \begin{matrix} \boxed{\nu_{\tau R}} \\ \tau_R \end{matrix}$

- Standard Model extension: $\nu_R \Rightarrow$ Dirac mass term $\mathcal{L}_{\mathrm{D}} \sim m_{\mathrm{D}} \overline{\nu_L} \nu_R$
- This is Standard Model physics, because m_{D} is generated by the standard Higgs mechanism:

$$y \overline{L_L} \widetilde{\Phi} \nu_R \quad \xrightarrow[\text{Breaking}]{\text{Symmetry}} \quad y v \overline{\nu_L} \nu_R \quad \Rightarrow \quad m_{\mathrm{D}} \sim y v$$

- Bad: extremely small Yukawa couplings: $y \lesssim 10^{-11}$

Beyond the Standard Model

- The introduction of ν_R leads us beyond the Standard Model because they can have the Majorana mass term

  $$\mathcal{L}_{\mathrm{M}} \sim m_{\mathrm{M}} \overline{\nu_R} \nu_R^c \qquad \text{singlet under SM symmetries!}$$

- This is beyond the Standard Model because m_{M} is not generated by the Higgs mechanism of the Standard Model $\Rightarrow$ new physics is required.

- The Majorana mass term can be avoided by imposing lepton number conservation which should anyway be explained by some physics beyond the Standard Model.

Seesaw Mechanism

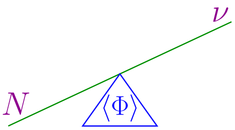
without lepton number conservation

$$\mathcal{L}^{\text{D+M}} = -\frac{1}{2} \begin{pmatrix} \overline{\nu_L^c} & \overline{\nu_R} \end{pmatrix} \begin{pmatrix} 0 & m_{\text{D}} \\ m_{\text{D}} & m_{\text{M}} \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} + \text{H.c.}$$

m_{M} can be arbitrarily large (not protected by SM symmetries)

$m_{\text{M}} \sim$ scale of new physics beyond Standard Model $\Rightarrow m_{\text{M}} \gg m_{\text{D}}$

diagonalization of $\begin{pmatrix} 0 & m_{\text{D}} \\ m_{\text{D}} & m_{\text{M}} \end{pmatrix} \Longrightarrow m_\nu \simeq \frac{m_{\text{D}}^2}{m_{\text{M}}} \qquad m_N \simeq m_{\text{M}}$



seesaw mechanism

natural explanation of smallness
of light neutrino masses

massive neutrinos are Majorana $\Rightarrow$ $\boxed{\beta\beta_{0\nu}}$

$$\nu \simeq -i \left(\nu_L - \nu_L^c\right) \qquad N \simeq \nu_R + \nu_R^c$$

3-GEN $\Rightarrow$ effective low-energy 3-ν mixing

Majorana Neutrinos

There are compelling arguments in favor of Majorana Neutrinos:

- A Majorana field is simpler than a Dirac field: it corresponds to the fundamental spinor representation of the Lorentz group.
  A Dirac field is more complicated: it is made of two Majorana fields degenerate in mass.
  If there is no additional constraint (as L conservation), a neutral elementary particle as the neutrino is naturally Majorana.
- The seesaw mechanism if ν_R is introduced to generate neutrino masses.
- A general Effective Field Theory argument from high-energy new physics:

$$\mathscr{L} = \mathscr{L}_{\text{SM}} + \frac{g_5}{\mathcal{M}}\,\mathscr{O}_5 + \frac{g_6}{\mathcal{M}^2}\,\mathscr{O}_6 + \ldots$$

  - $\mathscr{O}_5$: Majorana neutrino masses (Lepton number violation and $\beta\beta_{0\nu}$ decay).

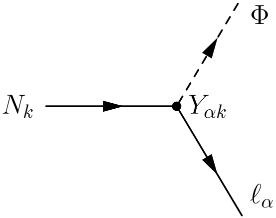
$$\mathscr{O}_5 = (\overline{L}\,\widetilde{\Phi})\,(\widetilde{\Phi}^T L^c) \qquad L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix} \qquad \widetilde{\Phi} = \begin{pmatrix} \phi_0 \\ -\phi_+ \end{pmatrix}$$

  - $\mathscr{O}_6$: Baryon number violation (proton decay)
    and Neutrino Non-Standard Interactions (NSI).

Leptogenesis

- Off-equilibrium L and CP violating heavy Majorana neutrino decays at $T \sim M_N$:

$$\mathcal{L}_I \sim \overline{L}\,\widetilde{\Phi}\,Y\,\nu_R$$



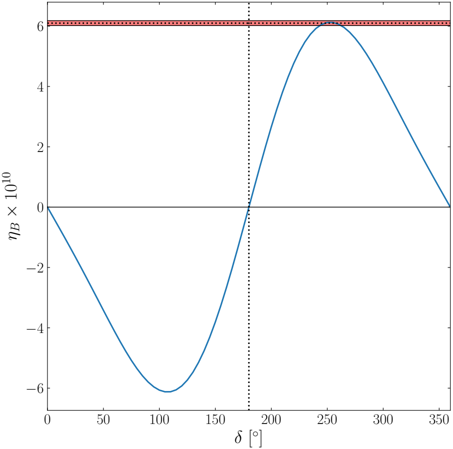
$$A_L \sim \frac{\sum_{k,\alpha}\left[\Gamma(N_k \to \Phi\ell_\alpha) - \Gamma(N_k \to \bar{\Phi}\bar{\ell}_\alpha)\right]}{\sum_{k,\alpha}\left[\Gamma(N_k \to \Phi\ell_\alpha) + \Gamma(N_k \to \bar{\Phi}\bar{\ell}_\alpha)\right]}$$

- The lepton asymmetry A_L is converted into a baryon asymmetry A_B at $T \sim 100\,\text{GeV}$ by electroweak sphalerons that conserve $B - L$ and break $B + L$.

- Seesaw $\Rightarrow$ $Y \sim \frac{1}{v}\,\underbrace{M_R^{1/2}\,R}_{\text{inaccessible}}\,\underbrace{m_\nu^{1/2}\,U_{3\times3}}_{\text{measurable}}$ $\qquad (RR^T = 1)$

  [Casas, Ibarra, NPB 618 (2001) 171]

- CP-violating $U_{3\times3}$ $\Rightarrow$ plausible CP-violating Y



$M_1 \simeq 5 \times 10^{10}$ GeV

$M_1 \ll M_1 \ll M_3$

[Moffat, Pascoli, Petcov, Turner, JHEP 1903, 034]

- The discovery of L violation ($\beta\beta_{0\nu}$ decay due to Majorana neutrinos) and CP violation in the lepton sector (through neutrino oscillations) would be a strong indication in favor of leptogenesis as the origin of the matter-antimatter asymmetry in the Universe.

- Seesaw with leptogenesis is a very attractive and compelling theory.
- However, in general there is no constraint on the number and mass scale of the ν_R's.
- It is possible and interesting that there is low-energy new physics (maybe connected with dark matter).
- Light fermions beyond the Standard Model are neutral and can mix with neutrinos: they are ν_R's.
- Light left-handed anti-ν_R are light sterile neutrinos

$$\nu_R^c \to \nu_{sL} \qquad \text{(left-handed)}$$

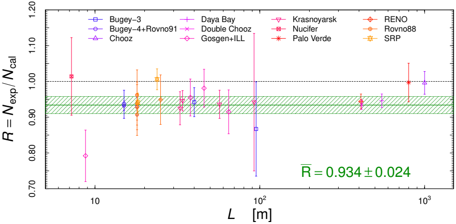
- Sterile means no standard model interactions

[Pontecorvo, Sov. Phys. JETP 26 (1968) 984]

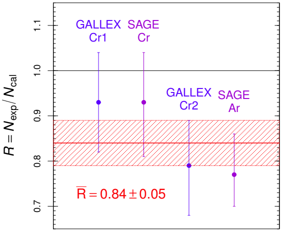
Light Sterile Neutrinos

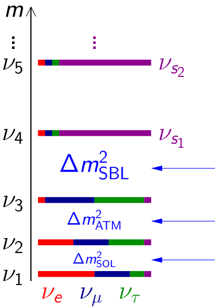
Short-Baseline Anomalies

Reactor Anomaly: $\bar{\nu}_e \to \bar{\nu}_x$ $(\sim 3\sigma)$



Gallium Anomaly: $\nu_e \to \nu_x$ $(\sim 3\sigma)$





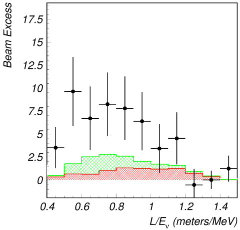
$\gtrsim 1\,\text{eV}^2$

$\simeq 2.5 \times 10^{-3}\,\text{eV}^2$

$\simeq 7.4 \times 10^{-5}\,\text{eV}^2$

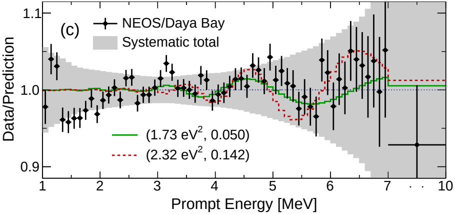
$$\boxed{L^{\text{osc}} = \frac{4\pi E}{\Delta m^2}}$$

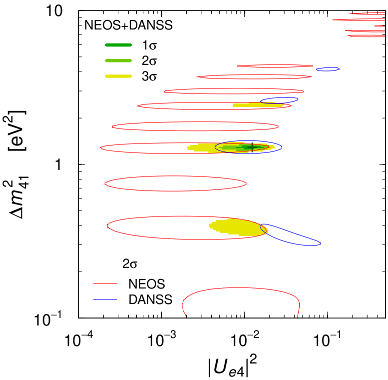
LSND Anomaly: $\bar{\nu}_\mu \to \bar{\nu}_e$ $(\sim 4\sigma)$



Reactor Spectral Ratios

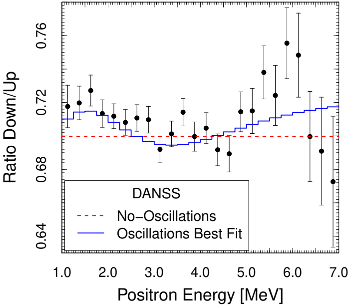
NEOS [PRL 118 (2017) 121802 (arXiv:1610.05134)]





DANSS

[PLB 787 (2018) 56, arXiv:1804.04046]

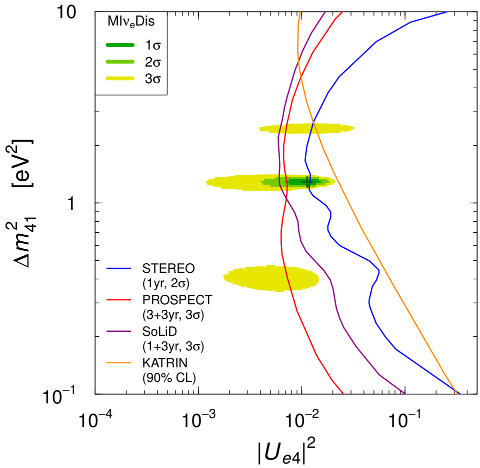


MODEL INDEPENDENT!

$\sim 3.5\sigma$

[Gariazzo, CG, Laveder, Li, arXiv:1801.06467]
[Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, arXiv:1803.10661]

Model-Independent ν_e and $\bar{\nu}_e$ Disappearance



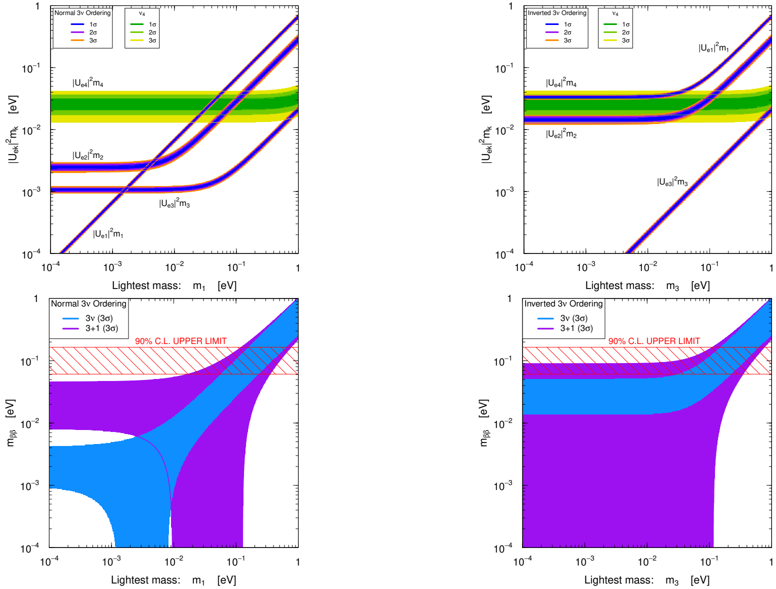
$$\Delta m^2_{41} = 1.29 \pm 0.03$$

$$|U_{e4}|^2 = 0.012 \pm 0.003$$

Huge potential for epochal New Physics discovery!

Neutrinoless Double-Beta Decay

$$m_{\beta\beta} = \left| |U_{e1}|^2 \, m_1 + |U_{e2}|^2 \, e^{i\alpha_{21}} \, m_2 + |U_{e3}|^2 \, e^{i\alpha_{31}} \, m_3 + |U_{e4}|^2 \, e^{i\alpha_{41}} \, m_4 \right|$$



Non-Standard Interactions

- Observable non-renormalizable effective NSI of left-handed neutrinos:

  Charged-Current-like NSI: $(\alpha, \beta = e, \mu, \tau)$

$$\mathcal{H}_{\text{NSI}}^{\text{CC}} = 2\sqrt{2} G_{\text{F}} V_{ud} \sum_{\alpha,\beta} \left(\overline{\ell_{\alpha L}} \gamma_\rho \nu_{\beta L}\right) \left[\varepsilon_{\alpha\beta}^{udL} \overline{u_L} \gamma^\rho d_L + \varepsilon_{\alpha\beta}^{udR} \overline{u_R} \gamma^\rho d_R\right] + \text{H.c.}$$

$$+ 2\sqrt{2} G_{\text{F}} \sum_{\alpha,\beta} \left(\overline{\nu_{\alpha L}} \gamma_\rho \nu_{\beta L}\right) \sum_{\sigma \neq \delta} \left[\varepsilon_{\alpha\beta}^{\sigma\delta L} \overline{\ell_{\sigma L}} \gamma^\rho \ell_{\delta L} + \varepsilon_{\alpha\beta}^{\sigma\delta R} \overline{\ell_{\sigma R}} \gamma^\rho \ell_{\delta R}\right]$$

  Neutral-Current-like or Matter NSI: $(\varepsilon_{\alpha\beta}^{fP} = \varepsilon_{\beta\alpha}^{fP*})$

$$\mathcal{H}_{\text{NSI}}^{\text{NC}} = 2\sqrt{2} G_{\text{F}} \sum_{\alpha,\beta} \left(\overline{\nu_{\alpha L}} \gamma_\rho \nu_{\beta L}\right) \sum_{f=e,u,d} \left[\varepsilon_{\alpha\beta}^{fL} \overline{f_L} \gamma^\rho f_L + \varepsilon_{\alpha\beta}^{fR} \overline{f_R} \gamma^\rho f_R\right]$$

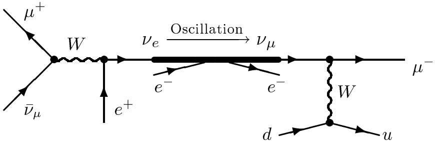
- Obtained in Effective Field Theory from operators of dimension 6 and higher:

$$\mathscr{O}_6 = \sum_{\alpha,\beta,\sigma,\delta} C_{\alpha\beta\sigma\delta} \left(\overline{L_\alpha} \gamma^\rho L_\beta\right) \left(\overline{L_\sigma} \gamma_\rho L_\delta\right) + \ldots$$

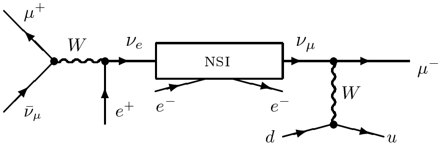
  Constraints are required to suppress unobserved large charged lepton transitions as $\mu \to 3e$. [see: Gavela, Hernandez, Ota, Winter, PRD 79 (2009) 013007]

NSI Effects on Oscillations

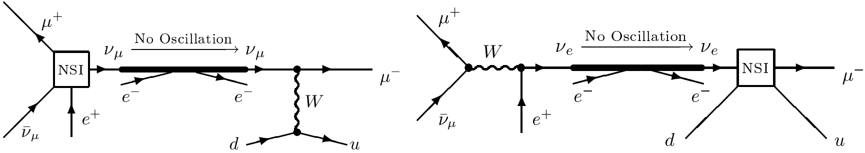
- Standard oscillations with matter effects:



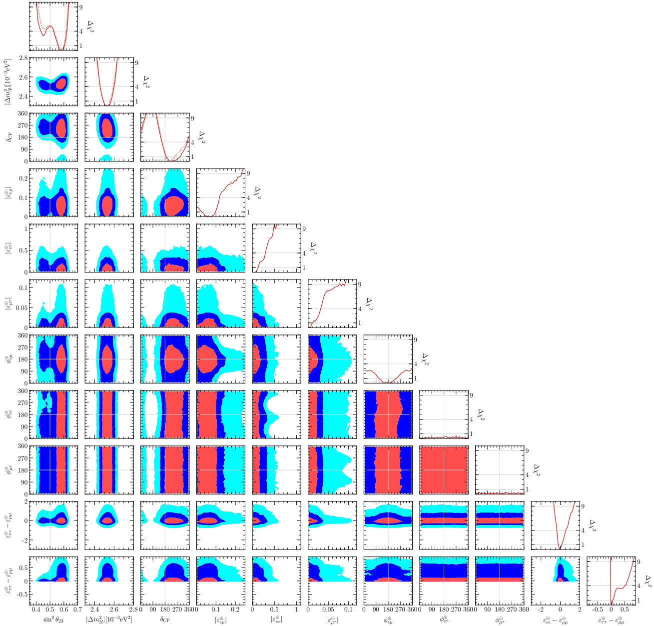
- NC NSI in neutrino propagation in matter $\sim \varepsilon$:



- CC NSI in neutrino production and detection $\sim \varepsilon^2$:



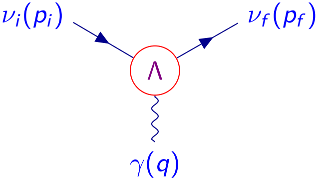
[Kopp, Lindner, Ota, PRD 76 (2007) 013001]



[Esteban, Gonzalez-Garcia, Maltoni, JHEP 1906 (2019) 055, arXiv:1905.05203]

Electromagnetic Interactions

- Effective Hamiltonian: $\mathcal{H}_{\text{em}}^{(\nu)}(x) = j_\mu^{(\nu)}(x) A^\mu(x) = \sum_{k,j=1} \overline{\nu_k}(x) \Lambda_\mu^{kj} \nu_j(x) A^\mu(x)$
- Effective electromagnetic vertex:



$$\langle \nu_f(p_f) | j_\mu^{(\nu)}(0) | \nu_i(p_i) \rangle = \overline{u_f}(p_f) \Lambda_\mu^{fi}(q) u_i(p_i)$$

$$q = p_i - p_f$$

- Vertex function:

$$\Lambda_\mu(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right) \left[F_Q(q^2) + F_A(q^2) q^2 \gamma_5\right] - i \sigma_{\mu\nu} q^\nu \left[F_M(q^2) + i F_E(q^2) \gamma_5\right]$$

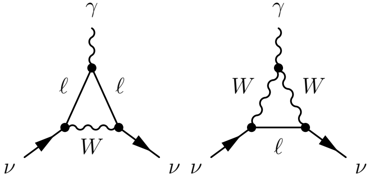
Lorentz-invariant form factors:	charge	anapole	magnetic	electric
$q^2 = 0 \quad \Longrightarrow$	$\mathfrak{q}$	a	μ	ε

Neutrino Charge Radii

- In the Standard Model neutrinos are neutral and there are no electromagnetic interactions at the tree-level.

- Radiative corrections generate an effective electromagnetic interaction vertex

$$\Lambda_\mu(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right) F(q^2)$$



- $F(q^2) = \cancel{F(0)} + q^2 \left.\dfrac{dF(q^2)}{dq^2}\right|_{q^2=0} + \ldots = q^2 \dfrac{\langle r^2 \rangle}{6} + \ldots$

- In the Standard Model: [Bernabeu et al, PRD 62 (2000) 113012, NPB 680 (2004) 450]

$$\langle r^2_{\nu_\ell} \rangle_{\text{SM}} = -\frac{G_{\text{F}}}{2\sqrt{2}\pi^2}\left[3 - 2\log\left(\frac{m^2_\ell}{m^2_W}\right)\right]$$

$$\langle r^2_{\nu_e} \rangle_{\text{SM}} = -8.2 \times 10^{-33}\,\text{cm}^2$$
$$\langle r^2_{\nu_\mu} \rangle_{\text{SM}} = -4.8 \times 10^{-33}\,\text{cm}^2$$
$$\langle r^2_{\nu_\tau} \rangle_{\text{SM}} = -3.0 \times 10^{-33}\,\text{cm}^2$$

Experimental Bounds

Method	Experiment	Limit [cm^2]	CL	Year
Reactor $\bar{\nu}_e\, e^-$	Krasnoyarsk	$\lvert\langle r^2_{\nu_e}\rangle\rvert < 7.3 \times 10^{-32}$	90%	1992
	TEXONO	$-4.2 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 6.6 \times 10^{-32}$	90%	2009
Accelerator $\nu_e\, e^-$	LAMPF	$-7.12 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 10.88 \times 10^{-32}$	90%	1992
	LSND	$-5.94 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 8.28 \times 10^{-32}$	90%	2001
Accelerator $\nu_\mu\, e^-$	BNL-E734	$-5.7 \times 10^{-32} < \langle r^2_{\nu_\mu}\rangle < 1.1 \times 10^{-32}$	90%	1990
	CHARM-II	$\lvert\langle r^2_{\nu_\mu}\rangle\rvert < 1.2 \times 10^{-32}$	90%	1994

[see the review Giunti, Studenikin, RMP 87 (2015) 531, arXiv:1403.6344

and the update in Cadeddu, Giunti, Kouzakov, Y.F. Li, Studenikin, Y.Y. Zhang, PRD 98 (2018) 113010, arXiv:1810.05606]

- Neutrino charge radii contribute coherently to standard neutral-current weak interactions ⇒ shifts $\sin^2\vartheta_W \to \sin^2\vartheta_W \left(1 + \frac{1}{3} m_W^2 \langle r^2_{\nu_\ell}\rangle\right)$
- The current limits are not too far from the SM prediction: about 1 order of magnitude.
- Powerful precision test of the SM.
- A failure to measure the SM values would imply BSM physics!

Neutrino Magnetic and Electric Moments

- Extended Standard Model with right-handed neutrinos and $\Delta L = 0$:

$$\mu_{kk}^{\text{D}} \simeq 3.2 \times 10^{-19} \mu_{\text{B}} \left(\frac{m_k}{\text{eV}} \right) \qquad \varepsilon_{kk}^{\text{D}} = 0$$

$$\left. \begin{array}{r} \mu_{kj}^{\text{D}} \\ i\varepsilon_{kj}^{\text{D}} \end{array} \right\} \simeq -3.9 \times 10^{-23} \mu_{\text{B}} \left(\frac{m_k \pm m_j}{\text{eV}} \right) \sum_{\ell=e,\mu,\tau} U_{\ell k}^* U_{\ell j} \left(\frac{m_\ell}{m_\tau} \right)^2$$

off-diagonal moments are GIM-suppressed

[Fujikawa, Shrock, PRL 45 (1980) 963; Pal, Wolfenstein, PRD 25 (1982) 766; Shrock, NPB 206 (1982) 359; Dvornikov, Studenikin, PRD 69 (2004) 073001, JETP 99 (2004) 254]

- Extended Standard Model with Majorana neutrinos ($|\Delta L| = 2$):

$$\mu_{kj}^{\text{M}} \simeq -7.8 \times 10^{-23} \mu_{\text{B}} \, i \, (m_k + m_j) \sum_{\ell=e,\mu,\tau} \text{Im} \left[U_{\ell k}^* U_{\ell j} \right] \frac{m_\ell^2}{m_W^2}$$

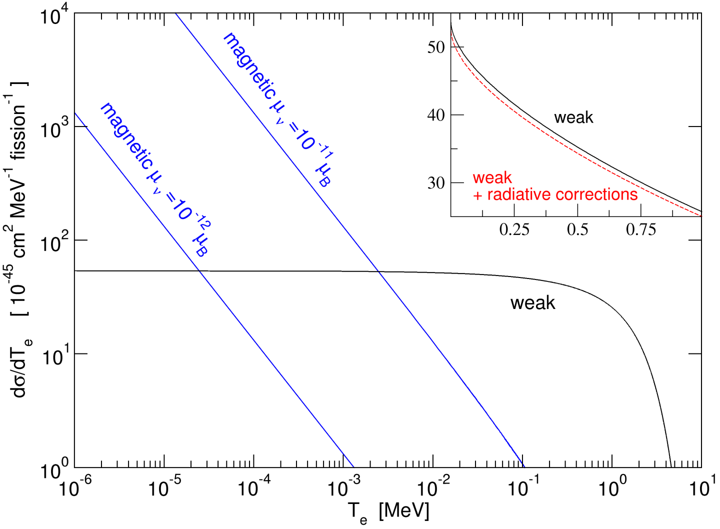
$$\varepsilon_{kj}^{\text{M}} \simeq 7.8 \times 10^{-23} \mu_{\text{B}} \, i \, (m_k - m_j) \sum_{\ell=e,\mu,\tau} \text{Re} \left[U_{\ell k}^* U_{\ell j} \right] \frac{m_\ell^2}{m_W^2}$$

[Shrock, NPB 206 (1982) 359]

GIM-suppressed, but additional model-dependent contributions of the scalar sector can enhance the Majorana transition dipole moments

[Pal, Wolfenstein, PRD 25 (1982) 766; Barr, Freire, Zee, PRL 65 (1990) 2626; Pal, PRD 44 (1991) 2261]

$$\left(\frac{d\sigma_{\nu e^-}}{dT_e}\right)_{\text{mag}} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)\left(\frac{\mu_\nu}{\mu_{\text{B}}}\right)^2$$



Method	Experiment	Limit $[\mu_{\mathrm{B}}]$	CL	Year
Reactor $\bar{\nu}_e\, e^-$	Krasnoyarsk	$\mu_{\nu_e} < 2.4 \times 10^{-10}$	90%	1992
	Rovno	$\mu_{\nu_e} < 1.9 \times 10^{-10}$	95%	1993
	MUNU	$\mu_{\nu_e} < 9 \times 10^{-11}$	90%	2005
	TEXONO	$\mu_{\nu_e} < 7.4 \times 10^{-11}$	90%	2006
	GEMMA	$\mu_{\nu_e} < 2.9 \times 10^{-11}$	90%	2012
Accelerator $\nu_e\, e^-$	LAMPF	$\mu_{\nu_e} < 1.1 \times 10^{-9}$	90%	1992
Accelerator $(\nu_\mu, \bar{\nu}_\mu)\, e^-$	BNL-E734	$\mu_{\nu_\mu} < 8.5 \times 10^{-10}$	90%	1990
	LAMPF	$\mu_{\nu_\mu} < 7.4 \times 10^{-10}$	90%	1992
	LSND	$\mu_{\nu_\mu} < 6.8 \times 10^{-10}$	90%	2001
Accelerator $(\nu_\tau, \bar{\nu}_\tau)\, e^-$	DONUT	$\mu_{\nu_\tau} < 3.9 \times 10^{-7}$	90%	2001
Solar $\nu_e\, e^-$	Super-Kamiokande	$\mu_{\mathrm{S}}(E_\nu \gtrsim 5\,\mathrm{MeV}) < 1.1 \times 10^{-10}$	90%	2004
	Borexino	$\mu_{\mathrm{S}}(E_\nu \lesssim 1\,\mathrm{MeV}) < 2.8 \times 10^{-11}$	90%	2017

[see the review Giunti, Studenikin, RMP 87 (2015) 531, arXiv:1403.6344]

- Gap of about 8 orders of magnitude between the experimental limits and the $\lesssim 10^{-19}\,\mu_{\mathrm{B}}$ prediction of the minimal Standard Model extensions.
- $\mu_\nu \gg 10^{-19}\,\mu_{\mathrm{B}}$ discovery $\Rightarrow$ non-minimal new physics beyond the SM.
- Neutrino spin-flavor precession in a magnetic field

[Lim, Marciano, PRD 37 (1988) 1368; Akhmedov, PLB 213 (1988) 64]

Conclusions

- Neutrinos can be powerful messengers of the physics beyond the SM.
- The discovery of L violation through $\beta\beta_{0\nu}$ decay is of paramount importance.
- The additional discovery of CP violation in the lepton sector in LBL neutrino oscillation experiments will represent a strong indication in favor of leptogenesis as the origin of the matter-antimatter asymmetry in the Universe.
- The search for sterile neutrinos may open a cornucopia of new phenomena.
- Look out for neutrino Non-Standard Interactions and Electromagnetic Interactions.