Non-Standard ν properties & searches (I)

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International Neutrino Summer School
University of Bologna - June 6th, 2024

Outline

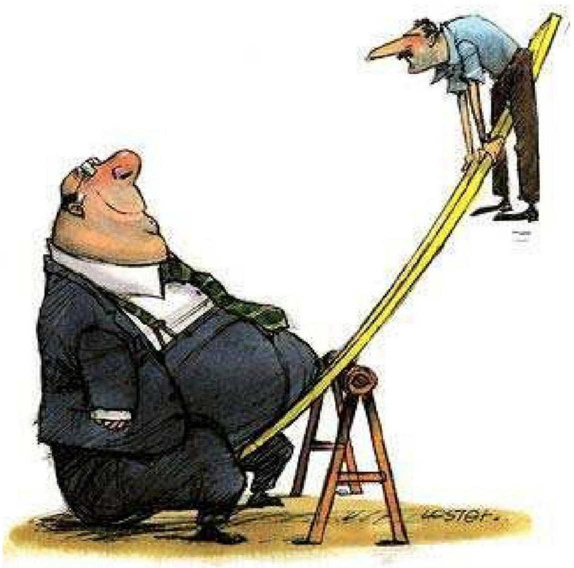
- Non-standard interactions: impact of NSI on oscillations
- Non-standard interactions: scattering (nuclear and electron)

- Non-Unitarity
- Sterile neutrinos in oscillations

Why BSM?

Experimental evidence:
Dark matter
Neutrino masses
Matter-antimatter asymmetry
Gravitational interaction

Theoretical indications:
Strong CP problem
Hierarchy problem
Flavor puzzle
Cosmological constant



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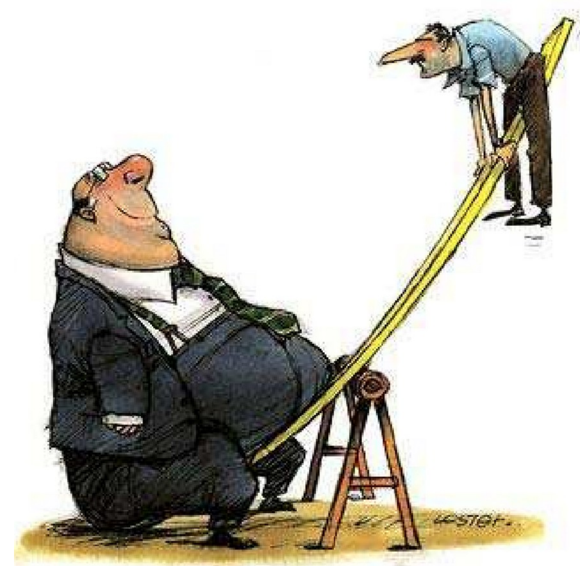
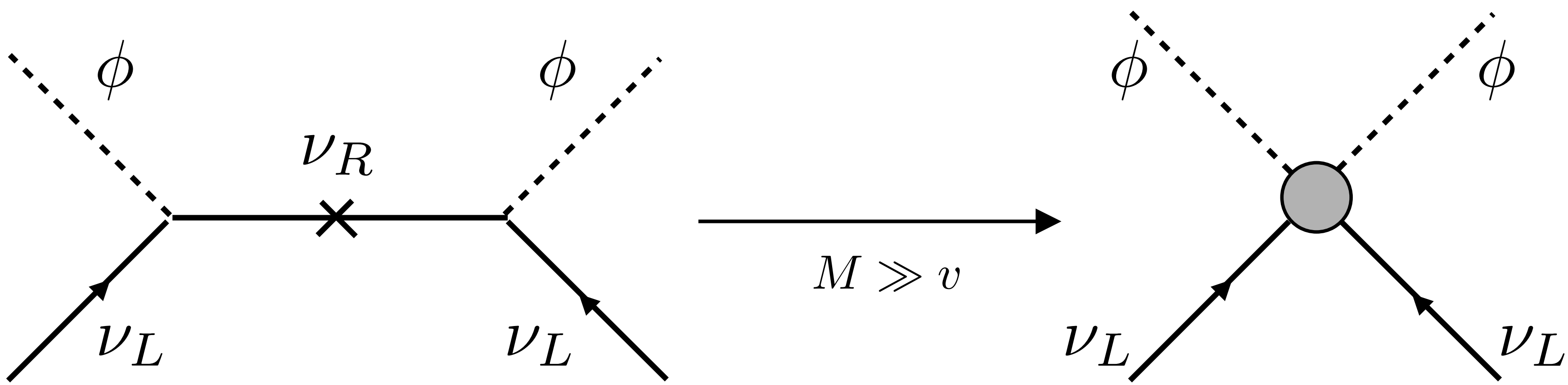


Neutrino masses

$$m_\nu \propto \frac{Y_\nu^2 v^2}{M}$$



Covered in S. Petcov's lectures

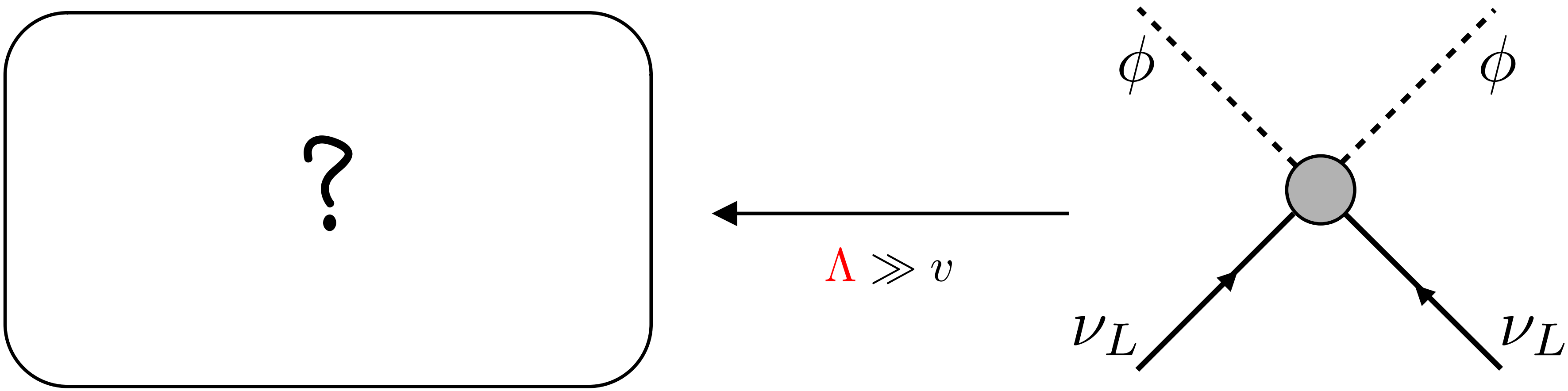
$$\propto \frac{1}{M}(\overline{L}_L\widetilde{\phi})(\widetilde{\phi}^t L_L^c)$$

Weinberg, 1979

Type I Seesaw:
Minkowski '77, Gell-Mann, Ramond, Slansky '79, Yanagida '79, Mohapatra, Senjanovic '80

Neutrino masses

$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\delta\mathcal{L}^{d=5} + \frac{1}{\Lambda^2}\delta\mathcal{L}^{d=6} + \ldots$$



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$$\propto \frac{1}{\Lambda}(\overline{L}_L\widetilde{\phi})(\widetilde{\phi}^t L_L^c)$$

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Neutrino Interactions: Fermi theory

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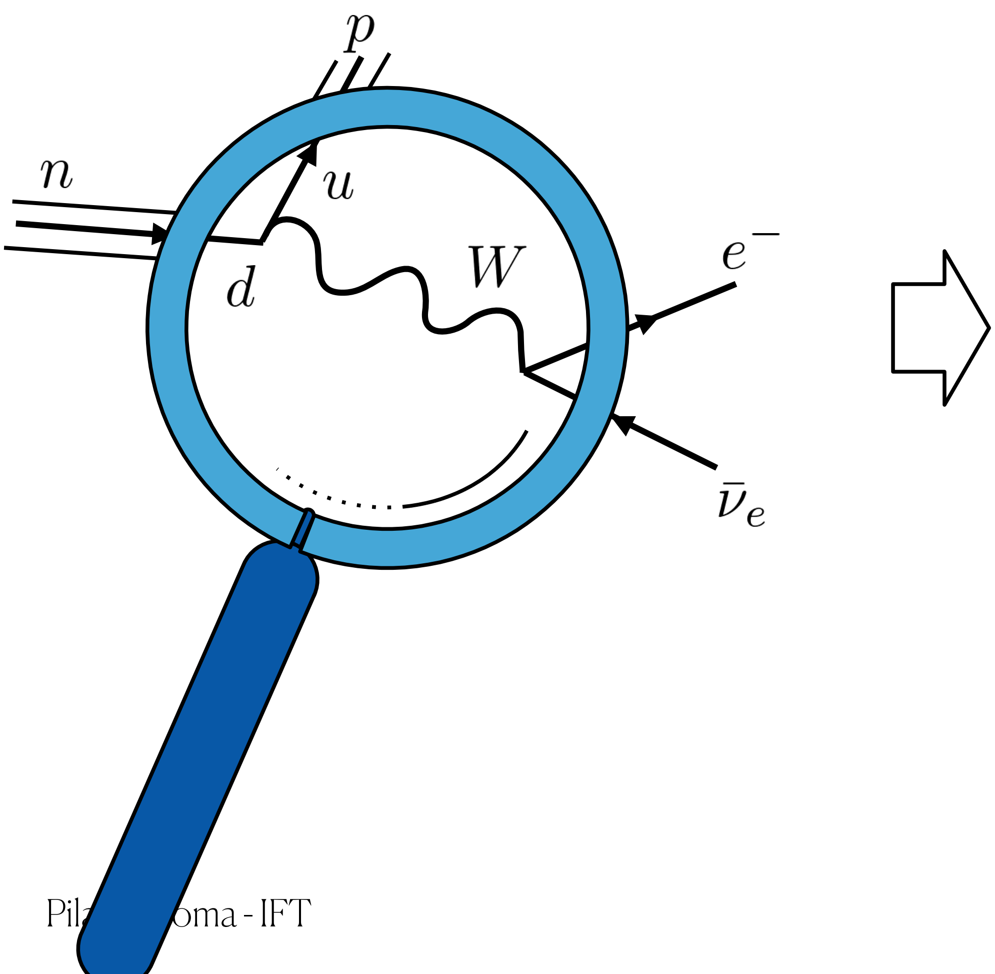

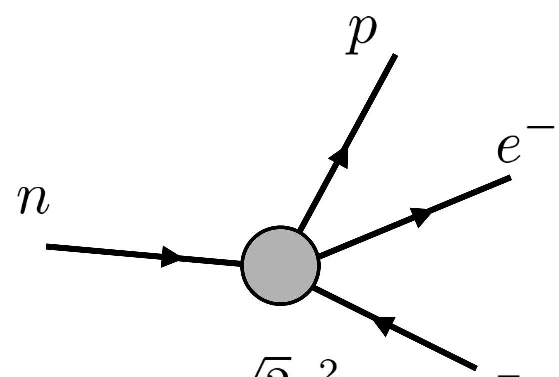

$$G_F = \frac{\sqrt{2}g^2}{8M_W^2}$$

Non-Standard Interactions

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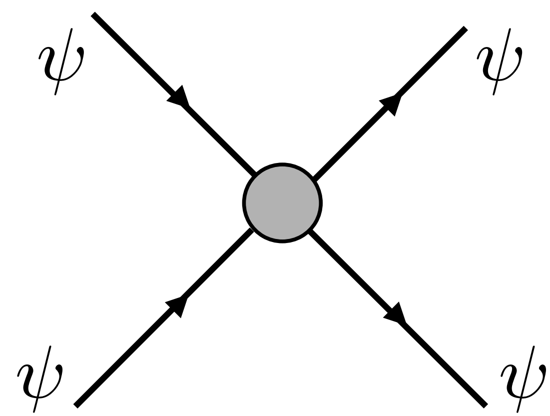

$$G_x \sim \frac{g^2}{\Lambda^2}$$

Wolfenstein '78; Mikheev & Smirnov '85; Valle '87; Roulet '91; Guzzo, Masiero, Petcov '91; ...

Non-Standard Interactions

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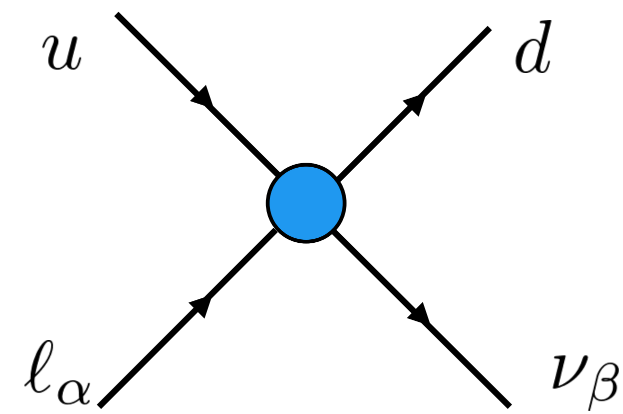
Charged-current-like:



$$-2\sqrt{2}G_F\varepsilon_{\alpha\beta}^{ff',P}\left(\overline{f}\gamma^\rho P f'\right)\left(\overline{\ell}_\alpha\gamma_\rho P_L\nu_\beta\right)$$

$$\varepsilon \sim \mathcal{O}(G_x/G_F)$$

Non-Standard Interactions

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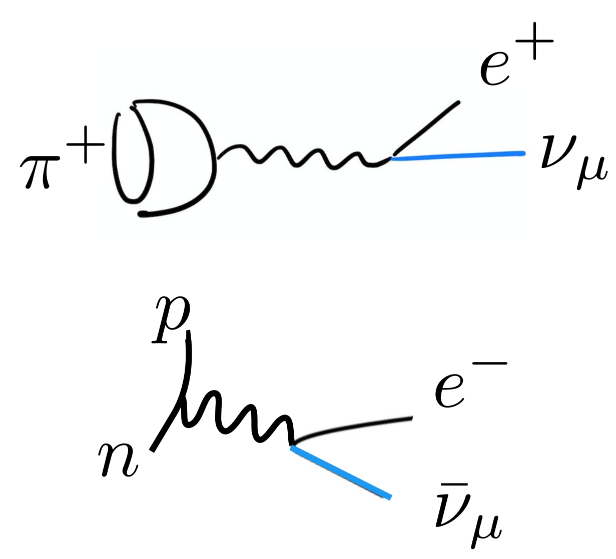
Charged-current-like:

NSI affecting
production/detection



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In full generality, all possible Lorentz structures are allowed. For CC-like operators:

$$\begin{aligned}\delta\mathcal{L}^{d=6} \supset & -2\sqrt{2}G_F V_{jk}\Big\{[\mathbf{1}+\epsilon_L^{jk}]_{\alpha\beta}(\bar{u}^j\gamma^\mu P_L d^k)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta) \\ & + [\epsilon_R^{jk}]_{\alpha\beta}(\bar{u}^j\gamma^\mu P_R d^k)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta)\Big\}\end{aligned}$$

Analogous to the ones in the SM

Non-Standard Interactions

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& + \frac{1}{2}[\epsilon_S^{jk}]_{\alpha\beta}(\bar{u}^j d^k)(\bar{\ell}_\alpha P_L\nu_\beta) \\
& - \frac{1}{2}[\epsilon_P^{jk}]_{\alpha\beta}(\bar{u}^j\gamma_5 d^k)(\bar{\ell}_\alpha P_L\nu_\beta) \\
& + \frac{1}{4}[\epsilon_T^{jk}]_{\alpha\beta}(\bar{u}^j\sigma^{\mu\nu}P_L d^k)(\bar{\ell}_\alpha\sigma_{\mu\nu}P_L\nu_\beta) + \text{h.c.}\Big\}
\end{aligned}$$

Other Lorentz structures are also possible

See e.g. the discussion in Falkowski, Gonzalez-Alonso, Tabrizi, 1910.02971; Falkowski et al, 2105.12136; Cherchiglia & Santiago, 2309.15924

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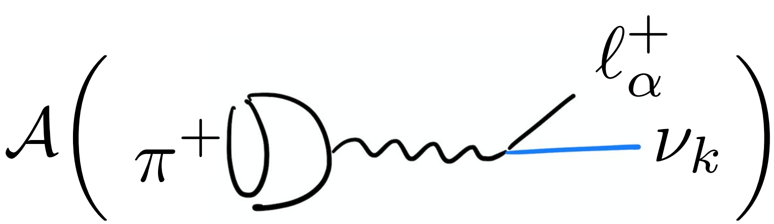

$$\propto [\mathcal{P}U]^*_{\alpha k} \left(\bar{u}_{\nu_k} P_L v_{\ell_\alpha}\right)$$

$$\mathcal{P}_{\alpha\beta} \equiv \delta_{\alpha\beta}$$ (in the SM)

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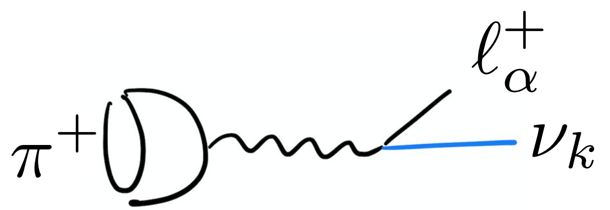
$\mathcal{A}\Big($ 

$\Big) \propto [\mathcal{P}U]^*_{\alpha k}\,(\bar{u}_{\nu_k} P_L v_{\ell_\alpha})$

$$\mathcal{P}_{\alpha\beta} \equiv \delta_{\alpha\beta} + \epsilon^L_{\alpha\beta} - \epsilon^R_{\alpha\beta} - \epsilon^P_{\alpha\beta}\frac{m_\pi^2}{m_{\ell_\alpha}(m_u + m_d)}$$

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We can play the same game for **NC-like** operators:

$$\begin{aligned}\delta\mathcal{L}^{d=6} \supset & -2\sqrt{2}G_F\Big\{[\mathbf{1}g_V^f + \epsilon_V^f]_{\alpha\beta}(\bar{f}\gamma^\mu f)(\bar{\nu}_\alpha\gamma_\mu P_L\nu_\beta) \\ & + [\mathbf{1}g_A^f + \epsilon_A^f]_{\alpha\beta}(\bar{f}\gamma^\mu\gamma^5 f)(\bar{\nu}_\alpha\gamma_\mu P_L\nu_\beta) \\ & \dots\Big\}\end{aligned}$$

Analogous to the ones in the SM

$$g_V^f \equiv T_f^3 - 2Q_f\sin^2\theta_w \qquad \epsilon_V^f \equiv \epsilon_L^f + \epsilon_R^f$$

$$g_A^f \equiv -T_f^3 \qquad \epsilon_A^f \equiv \epsilon_L^f - \epsilon_R^f$$

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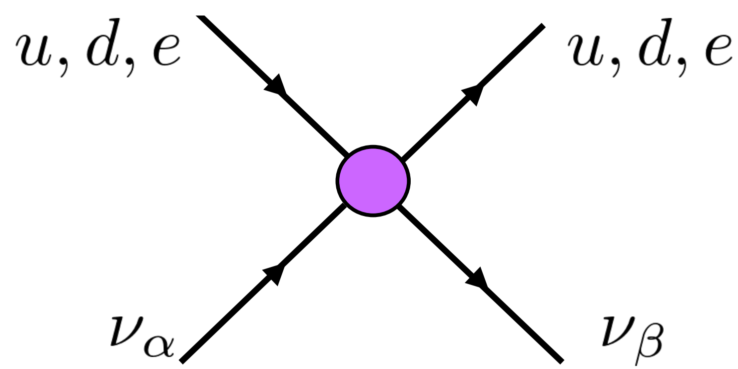
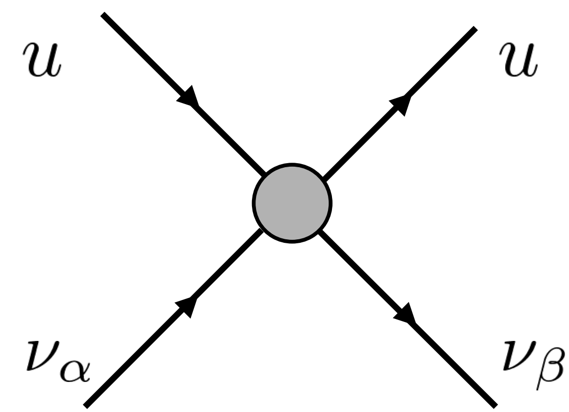


→ Has anyone noticed that I am cheating (a bit)?

Viable models for NSI at low energies

$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\delta\mathcal{L}^{d=5} + \frac{1}{\Lambda^2}\delta\mathcal{L}^{d=6} + \ldots$$



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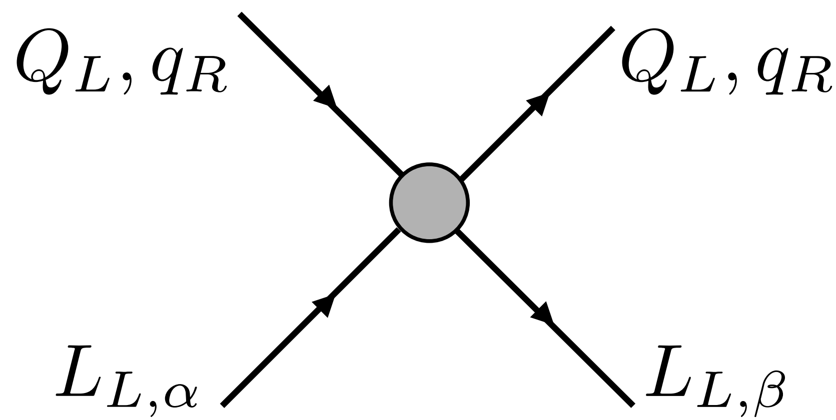


See e.g. Antusch, Baumann, Fernandez-Martinez, 0807.1003 [hep-ph]
Gavela, Hernandez, Ota, Winter, 0809.3451 [hep-ph]

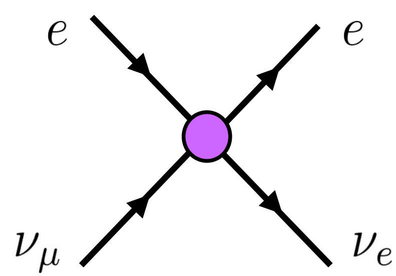
Viable models for NSI at low energies

For example, let us suppose I am interested in NSI with electrons.
These can be generated, e.g. through

$$[\mathcal{O}_{LE}]^{\beta}_{\alpha} = (\bar{L}^{\beta} e_R)(\bar{e}_R L_{\alpha})$$

After EWSB, this generates

$\bar{\nu}^{\beta}_{L} e_R \bar{e}_R \nu_{L\alpha}$ → the operator we want $\rightarrow [\epsilon^{e}_{R}]_{\alpha\beta}$



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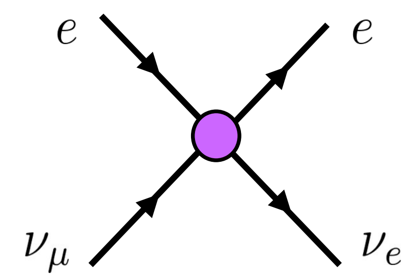
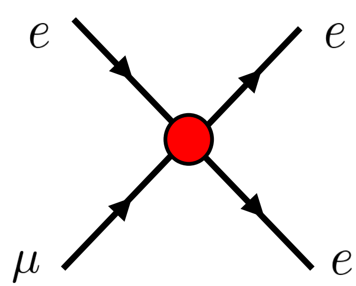


$\bar{\ell}^{\beta}_{L} e_R \bar{e}_R \ell_{L\alpha}$ → this is dangerous! e.g. $\mathrm{BR}(\mu \rightarrow 3e) < 10^{-12}$



Gavela, Hernandez, Ota, Winter, 0809.3451 [hep-ph]

Viable models for NSI at low energies

Possible ways out?

1) Generate NSI using higher-dimensional operators via Higgs insertions. For example:

$$\left.\begin{aligned}\left[\mathcal{O}^1_{LEH}\right]^{\beta\delta}_{\alpha\gamma} &= (\bar{L}^\beta \gamma^\rho L_\alpha)(\bar{E}^\delta \gamma_\rho E_\gamma)(H^\dagger H) \\ \left[\mathcal{O}^3_{LEH}\right]^{\beta\delta}_{\alpha\gamma} &= (\bar{L}^\beta \gamma^\rho \vec{\tau} L_\alpha)(\bar{E}^\delta \gamma_\rho E_\gamma)(H^\dagger \vec{\tau} H)\end{aligned}\right\} \text{At d=8}$$

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At d=8

These operators also generate the NSI operator and the charged-lepton companion, but through different combinations:

$$\delta\mathscr{L}_{\text{eff}} = \frac{1}{\Lambda^2}\left(-\frac{1}{2}\mathcal{C}_{LE} + \frac{v^2}{2\Lambda^2}(\mathcal{C}^{\mathbf{1}}_{LEH} + \mathcal{C}^{\mathbf{3}}_{LEH})\right)^{\alpha\gamma}_{\beta\delta} (\bar{\nu}^\beta \gamma^\rho \mathrm{P}_L \nu_\alpha)\,(\bar{\ell}^\delta \gamma_\rho \mathrm{P}_R \ell_\gamma)$$
$$+ \frac{1}{\Lambda^2}\left(-\frac{1}{2}\mathcal{C}_{LE} + \frac{v^2}{2\Lambda^2}(\mathcal{C}^{\mathbf{1}}_{LEH} - \mathcal{C}^{\mathbf{3}}_{LEH})\right)^{\alpha\gamma}_{\beta\delta} (\bar{\ell}^\beta \gamma^\rho \mathrm{P}_L \ell_\alpha)\,(\bar{\ell}^\delta \gamma_\rho \mathrm{P}_R \ell_\gamma) + \text{h.c.}$$

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- extra suppression with the scale of new physics → small effects expected
- a strong cancellation is needed in the charged lepton operator

Gavela, Hernandez, Ota, Winter, 0809.3451 [hep-ph]

Viable models for NSI at low energies

Possible ways out?

2) New Physics way below the electroweak scale → e.g., U(1)' with light Z' (~ tens of MeV)

See e.g., Farzan 1505.06906, Farzan & Shoemaker, 1512.09147, Farzan & Heeck, 1607.07616, Babu et al, 1705.01822

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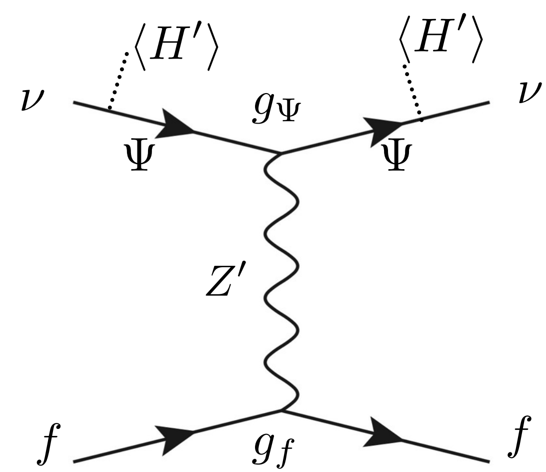
For example:

- New Dirac fermion, plus a Yukawa term with a new Higgs and the active neutrinos:

$$\mathcal{L} \supset y_\alpha \bar{L}_{L,\alpha} \tilde{H}' P_R \Psi_R + Z'_\mu (g_\ell \bar{L} \gamma^\mu P_L L + g_\Psi \bar{\Psi} \gamma^\mu \Psi)$$

$$\epsilon^f_{\alpha\beta} \sim \frac{g_f g_\Psi \kappa^*_\alpha \kappa_\beta}{G_F M^2_{Z'}}$$



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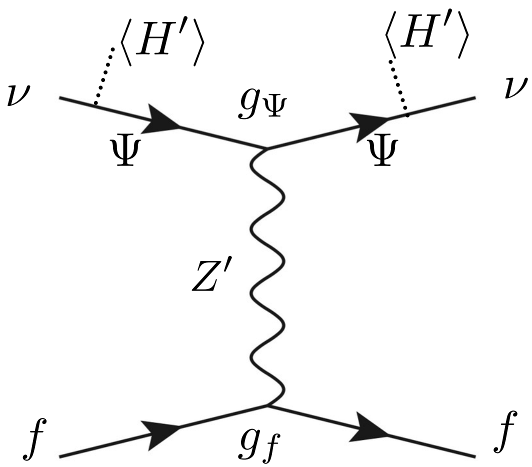
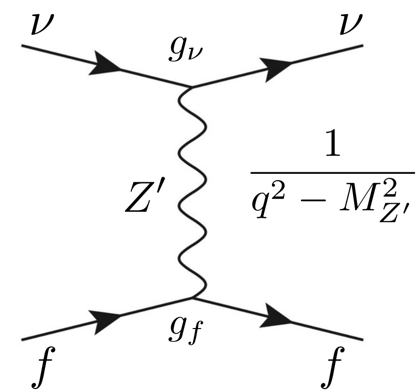


→ In this example, cLFV observables suppressed because they need the exchange of the new Higgs, which can be heavy

Light vs heavy mediators



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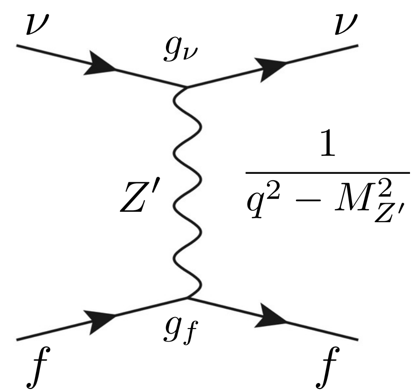

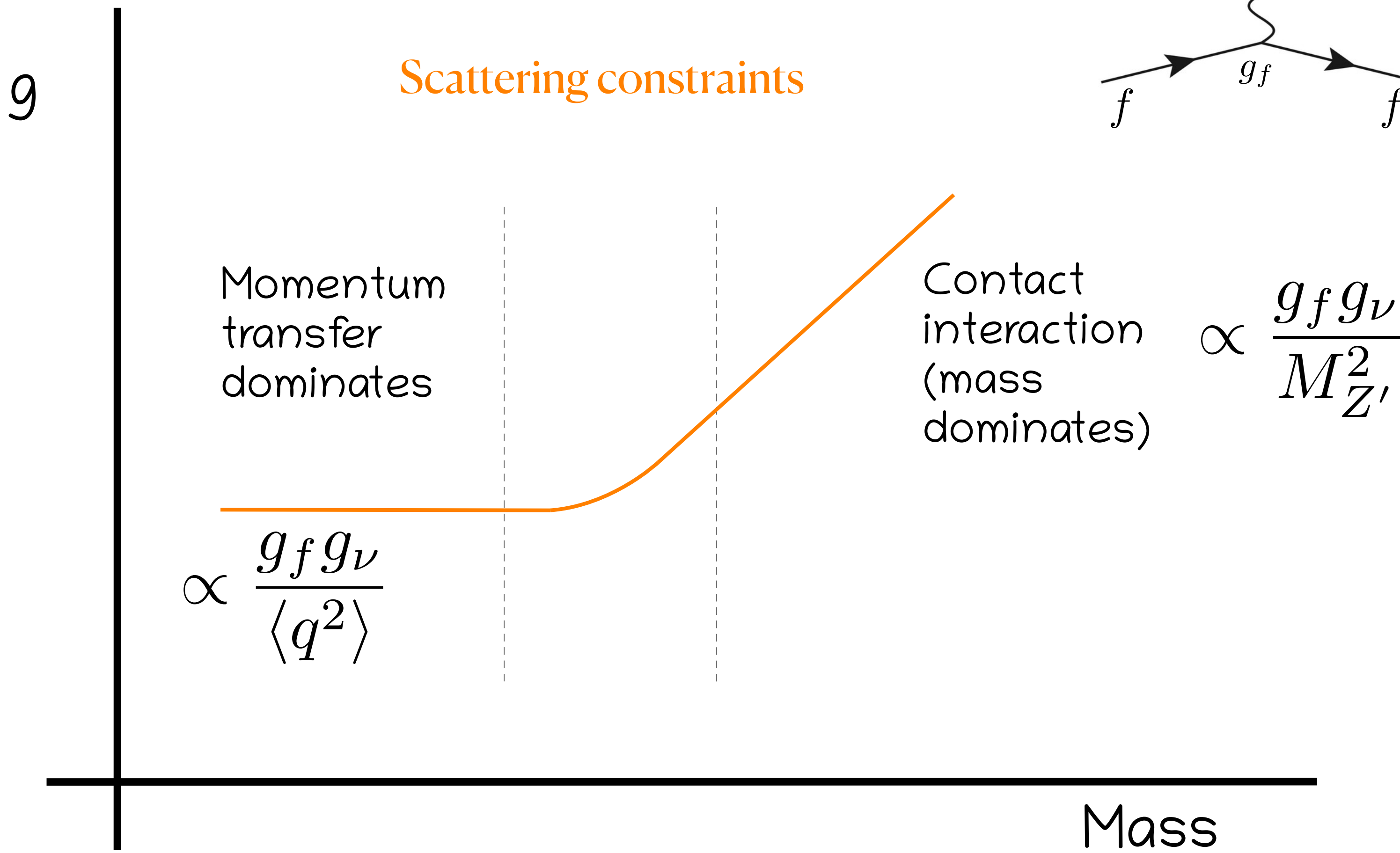

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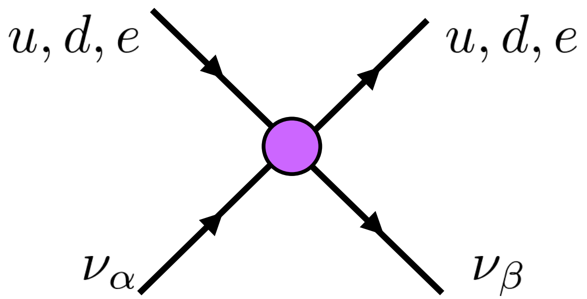

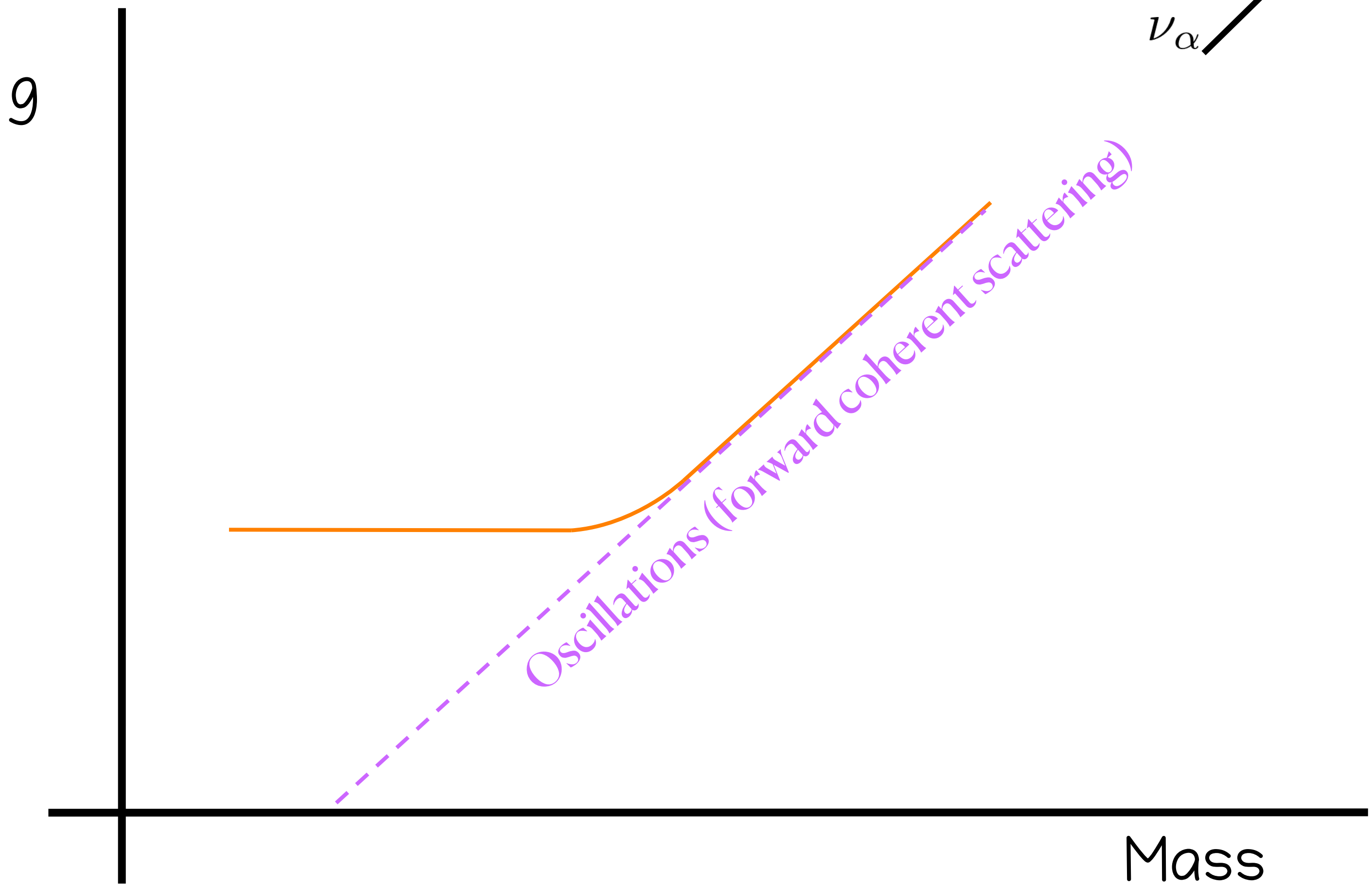

Model-independent bounds

The most relevant observables that give direct constraints at low energies are:

- Beta-decay
- Leptonic pion/kaon decays
- Hadronic tau decays
- Neutrino scattering:
  - CHARM/NuTeV ($\nu\, q \to \nu\, q$)
  - SNO ($\nu\, d \to \nu\, p\, n$)
  - Elastic scattering on electrons
  - Coherent scattering on nuclei
- Neutrino oscillations (impact on matter potential)

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Impact of NSI on oscillations (vector operators)

NSI in propagation

NSI in propagation will lead to a generalized matter potential affecting neutrino oscillations:

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[U\mathcal{H}_0U^\dagger + V_{cc}(x)\begin{pmatrix}1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau}\\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}\\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

$$V_{cc}(x) = 2\sqrt{2}G_F n_e(x)$$

Oscillations are only sensitive to vector NSI in the form:

$$\epsilon_{\alpha\beta}(x) \equiv \sum_{f,P}\frac{n_f(x)}{n_e(x)}\varepsilon_{\alpha\beta}^{fP} \quad \text{(f = u,d,e; P = L,R)}$$

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$$i\frac{d}{dt}\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \left[U\mathcal{H}_0U^\dagger + V_{cc}(x)\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}\right]\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

$$V_{cc}(x) = 2\sqrt{2}G_F n_e(x)$$

$$\downarrow$$

$$\begin{pmatrix} 1+(\epsilon_{ee}-\epsilon_{\mu\mu}) & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & 0 & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & (\epsilon_{\tau\tau}-\epsilon_{\mu\mu}) \end{pmatrix}$$

NSI in propagation

$$\mathcal{H} = U\mathcal{H}_0 U^\dagger + V_{\rm SM} + V_{\rm NSI}$$

$$\propto \frac{\Delta m^2}{2E} \qquad \propto G_F n_e(x) \qquad \propto G_F n_e(x)\epsilon_{\alpha\beta}$$

Reminder:

- Oscillations take place because the Hamiltonian is not diagonal in the flavor basis
- The oscillation pattern observed in atmospheric data and beam experiments has a characteristic dependence with L/E
- In the Sun things are different: the matter potential dominates at high-energies, due to the high density of electrons, while at low energies we get a constant transition probability (vacuum)

If NSI are large enough, they can dominate the Hamiltonian and do weird things, e.g.:

- suppress the oscillations (if NSI potential is diagonal in flavor basis)
- lead to oscillations, but with a pattern that does not match the usual L/E behaviour (for off-diagonal NSI)

LMA-Dark solution

The LMA solution

For solar neutrinos in the adiabatic regime: (see Lisi's lectures)

$$P_{ee} = \frac{1}{2}\left[1 + \cos 2\theta \cos 2\theta_M\right]$$ Parke '86

Effective mixing angle at neutrino production point inside the Sun (SM):

$$\cos 2\theta_m = \frac{\Delta m^2 \cos 2\theta - 2\sqrt{2} E G_F N_e}{\Delta m_m^2}$$

→ At high energies, we need $P_{ee} < 0.5$, so θ must be in the lower octant (LMA solution)

The LMA-dark solution

$$H_{\mathrm{NSI}} = \sqrt{2} G_F N_d \begin{pmatrix} 0 & \varepsilon \\ \varepsilon & \varepsilon' \end{pmatrix}$$

Effective mixing angle at neutrino production point inside the Sun (with NSI)

$$\cos 2\theta_M = \frac{\Delta m^2 \cos 2\theta - 2\sqrt{2} E G_F (N_e - \epsilon' N_d)}{\Delta m_M^2(\epsilon)}$$

Miranda, Tortola, Valle, hep-ph/0406280

The LMA-dark solution

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Bottom line: One can obtain $P_{ee} < 0.5$ even for $\cos 2\theta < 0$, as long as ε' is large enough → solar mixing angle in the upper octant!

Miranda, Tortola, Valle, hep-ph/0406280

The LMA-dark solution

For KamLAND, in the two-family approximation: (see Lisi's lectures)

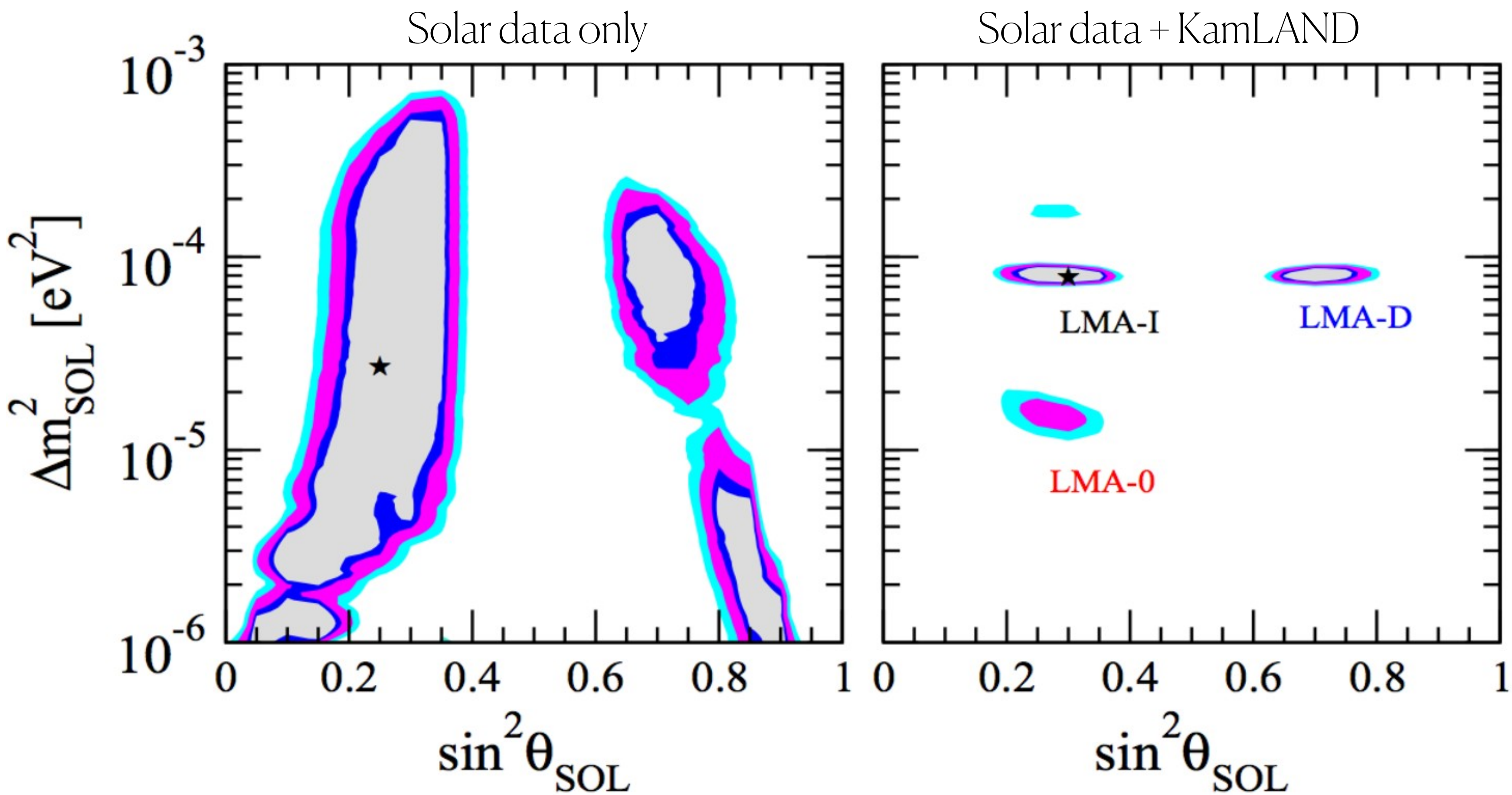
$$P_{ee} \simeq 1 - \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta m^2_{21} L}{4E} \right)$$

KamLAND results invariant under

$$\theta_{12} \leftrightarrow \pi/2 - \theta_{12}$$

Miranda, Tortola, Valle, hep-ph/0406280

The LMA-dark solution



Miranda, Tortola, Valle, hep-ph/0406280

Generalized mass ordering degeneracy

Using $U = O_{23}O_{13}V_{12}$

The vacuum Hamiltonian can be rewritten as:

$$H_{\text{vac}} = O_{23}O_{13}\begin{pmatrix} H^{(2)} & 0 \\ 0 & \Delta_{31} - \frac{\Delta_{21}}{2} \end{pmatrix} O_{13}^T O_{23}^T$$

$$H^{(2)} = \frac{\Delta_{21}}{2}\begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} e^{i\delta} \\ \sin 2\theta_{12} e^{-i\delta} & \cos 2\theta_{12} \end{pmatrix}$$

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Invariant under:

$$\Delta m^2_{31} \to -\Delta m^2_{31} + \Delta m^2_{21}$$
$$\sin\theta_{12} \leftrightarrow \cos\theta_{12}$$
$$\delta \to \pi - \delta$$

$$H \to -H^*$$

(see e.g., Gonzalez-Garcia, Maltoni, Salvado, 1103.4365)

Generalized mass ordering degeneracy

In the SM, the matter potential can break the sign degeneracy:

$$H = H_0 + H_{\rm mat}$$

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$$\sin\theta_{12} \leftrightarrow \cos\theta_{12}$$
$$\delta \to \pi - \delta$$

$$\epsilon_{ee} - \epsilon_{\mu\mu} \to -(\epsilon_{ee} - \epsilon_{\mu\mu}) - 2$$
$$\epsilon_{\tau\tau} - \epsilon_{\mu\mu} \to -(\epsilon_{\tau\tau} - \epsilon_{\mu\mu})$$
$$\epsilon_{\alpha\beta} \to -\epsilon^*_{\alpha\beta} \quad (\alpha \neq \beta)$$

$$H \to -H^*$$

The LMA-dark solution reappears here

PC and Schwetz, 1604.05772
Bakhti and Farzan, 1403.0744

Bounds from oscillations

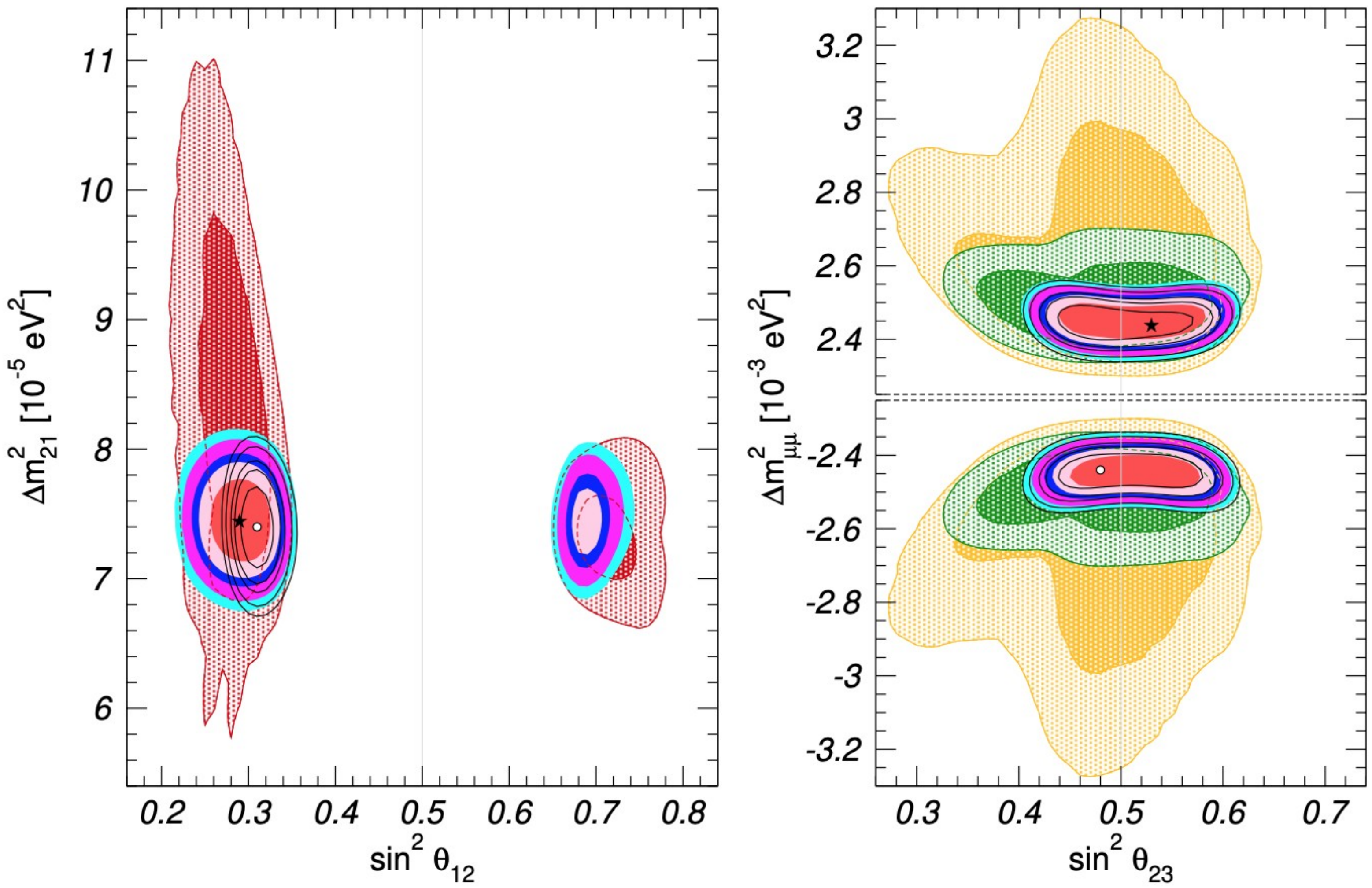


Figure from Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler and Salvado, 1805.04530

NSI effects on coherent scattering on nuclei

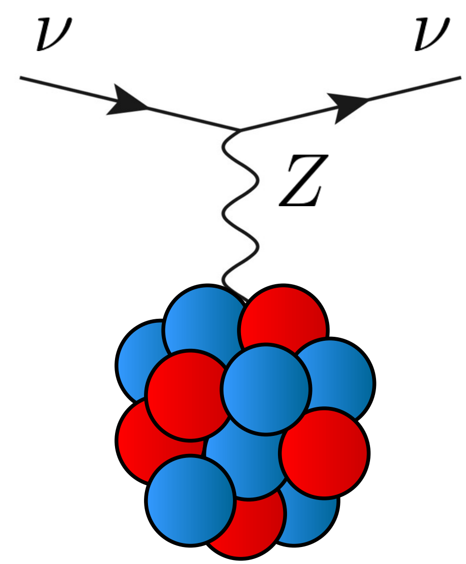
Coherent neutrino-nucleus scattering

In the SM:

$$\frac{d\sigma_\alpha}{dE_r} \simeq \frac{G_F^2}{2\pi}\frac{\mathcal{Q}_\alpha^2}{4}F_W^2(q^2)M\left(2-\frac{ME_r}{E_\nu^2}\right)$$

$$\mathcal{Q}_\alpha = Zg_p^V + Ng_n^V$$ (same for all flavors)

Freedman, PRD 9 (1974)



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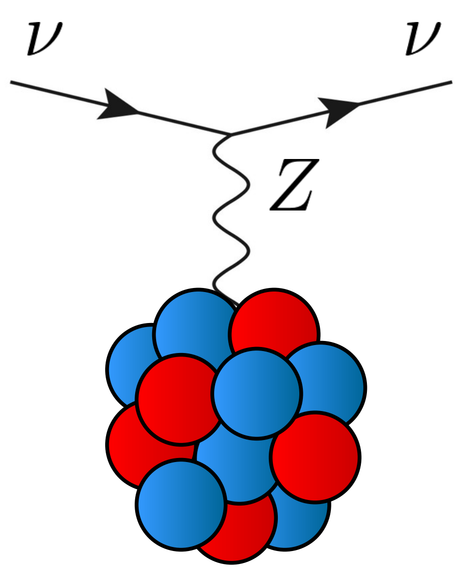
Freedman, PRD 9 (1974)

$$g_V^p = 1/2 - 2\sin^2\theta_w \sim 0.04$$
$$g_V^n = -1/2$$

⇨ $\sigma \propto N^2$



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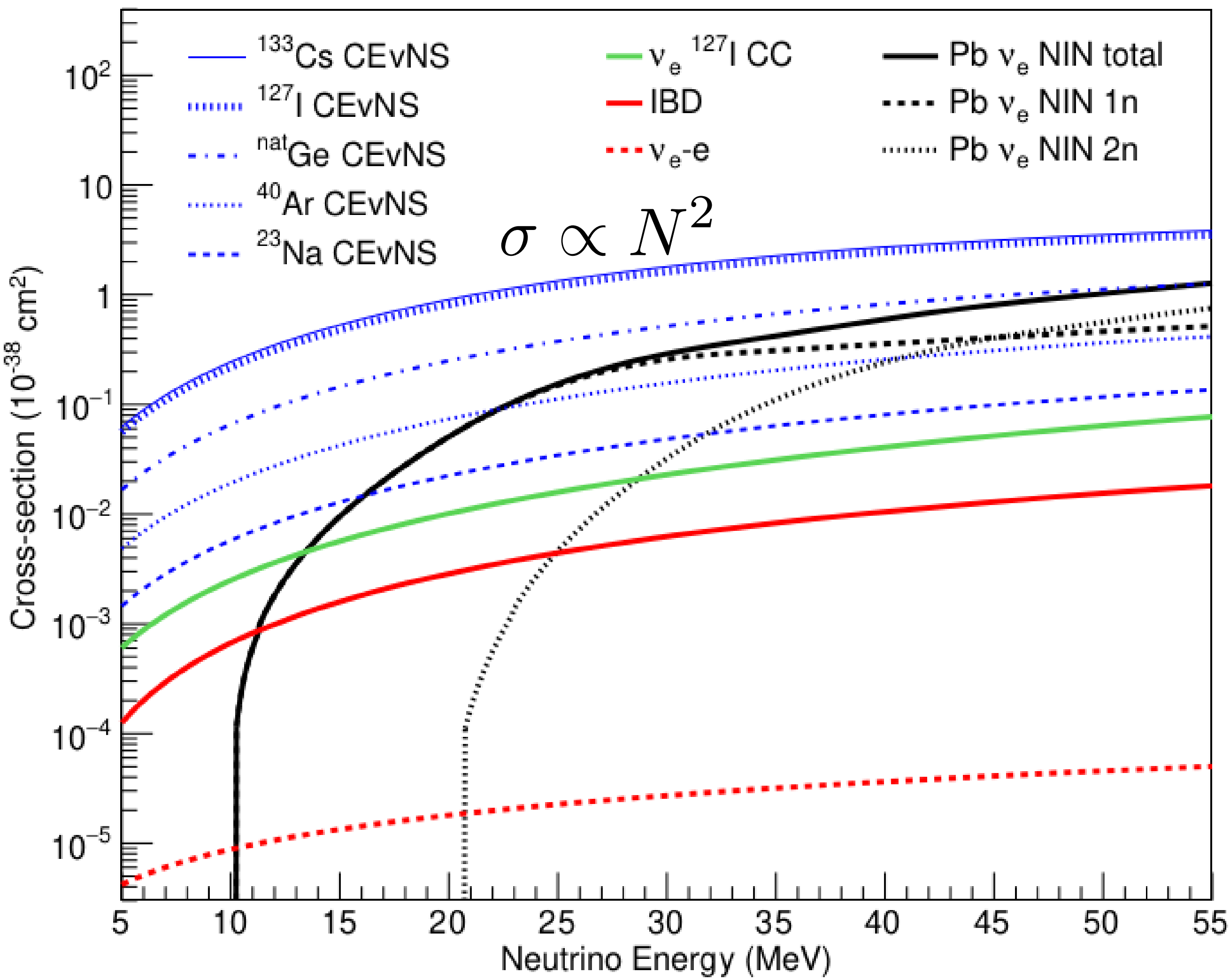

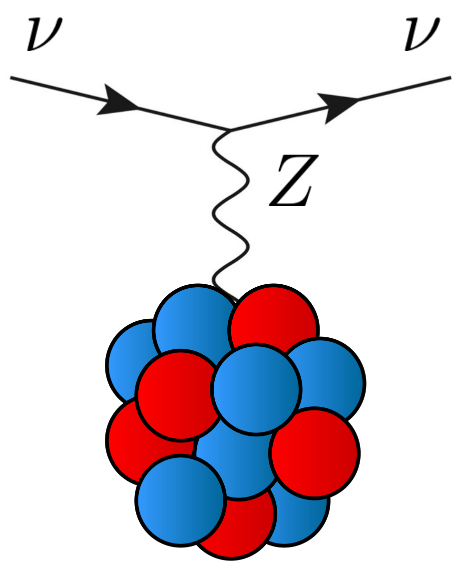

Figure from Scholberg, 1801.05546

Coherent neutrino-nucleus scattering

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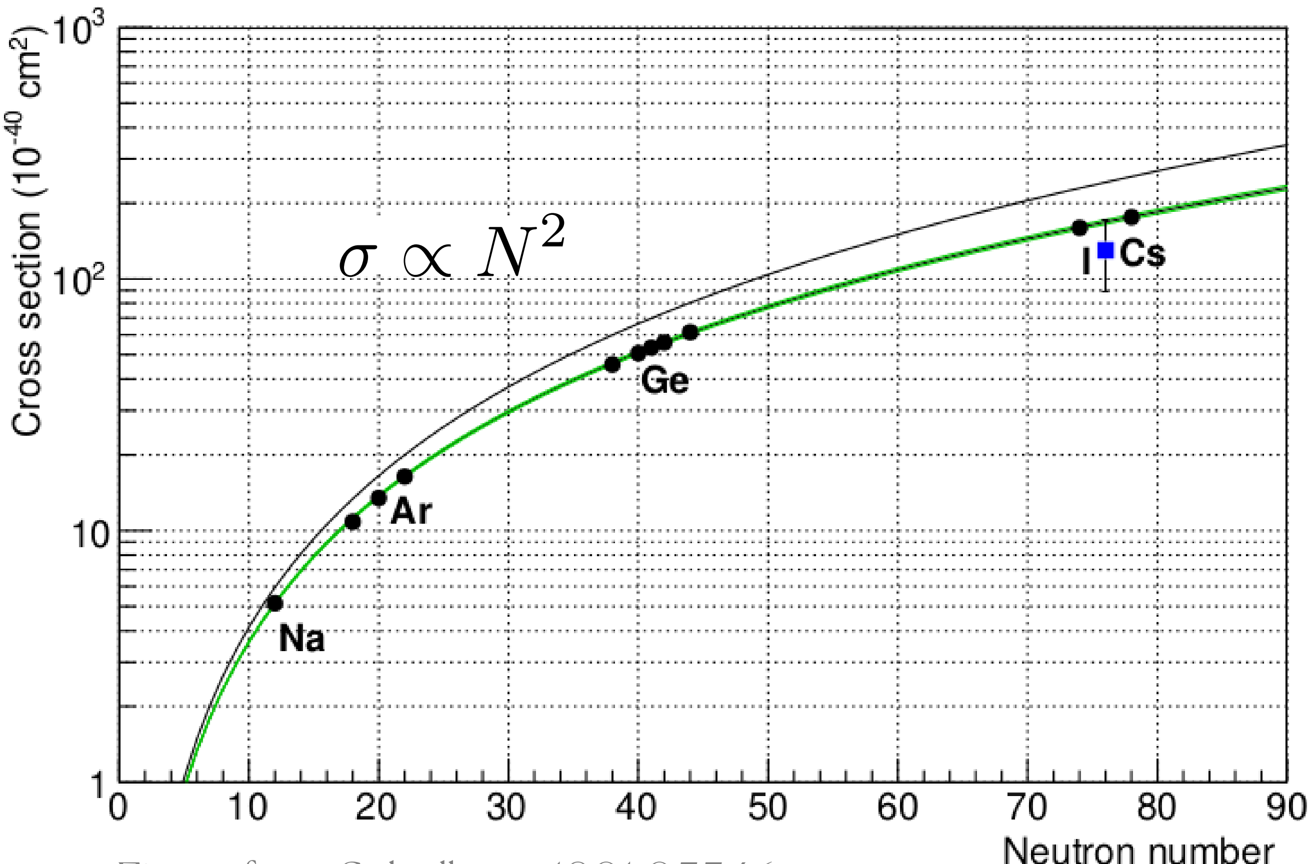

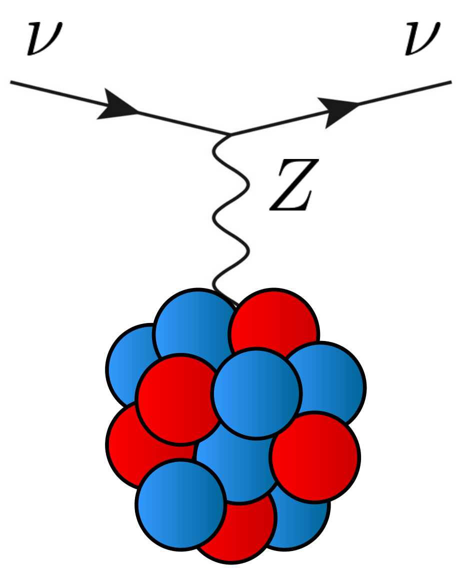

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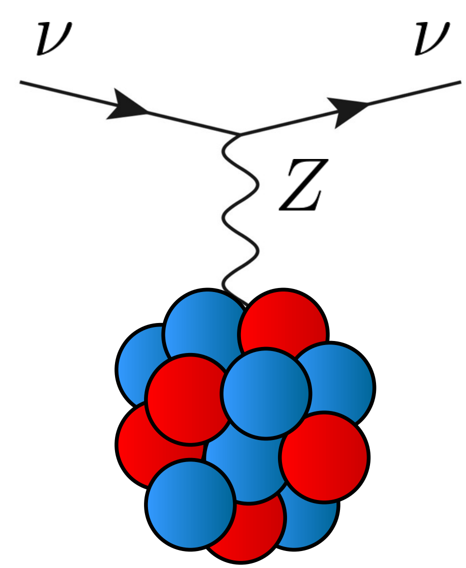

$$\mathcal{Q}_\alpha = Zg_p^V + Ng_n^V$$ (same for all flavors)

Freedman, PRD 9 (1974)

→ Then, why is it so challenging to observe?

Loss of coherence expected for momentum transfers: $q \sim \frac{1}{R}$

Coherent neutrino-nucleus scattering

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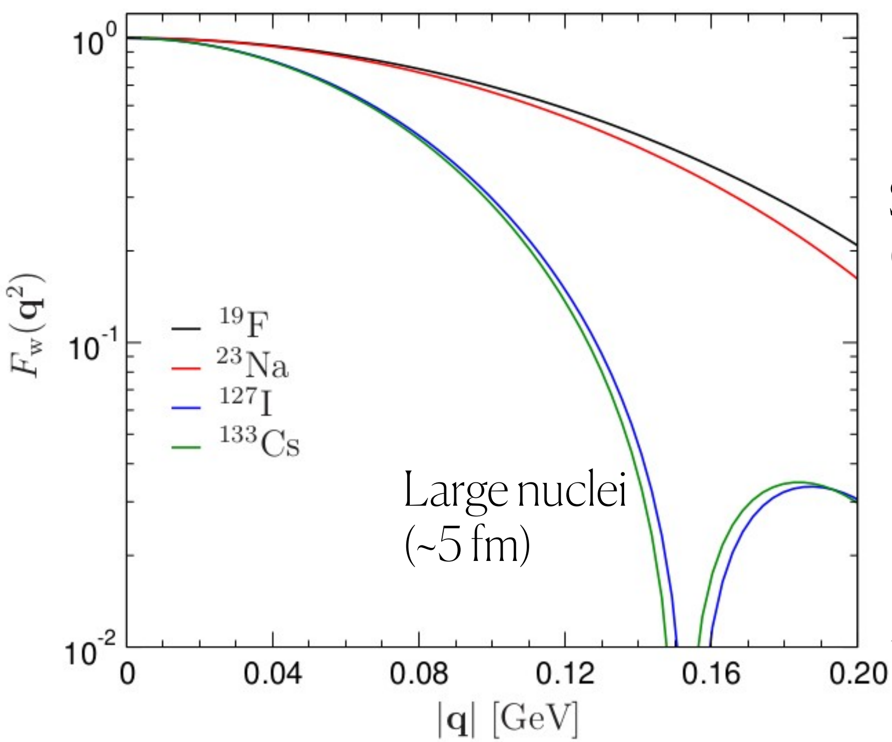
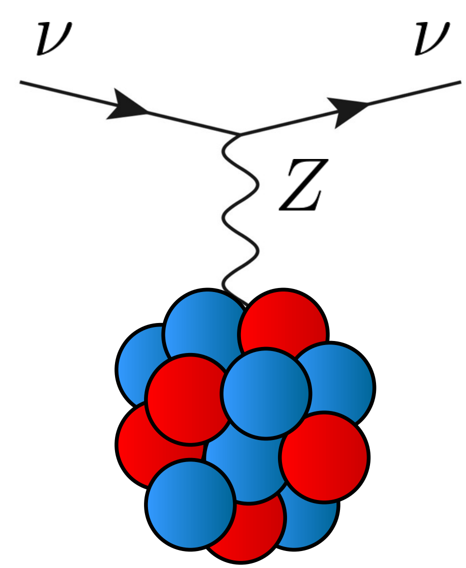


Small nuclei (~3 fm)

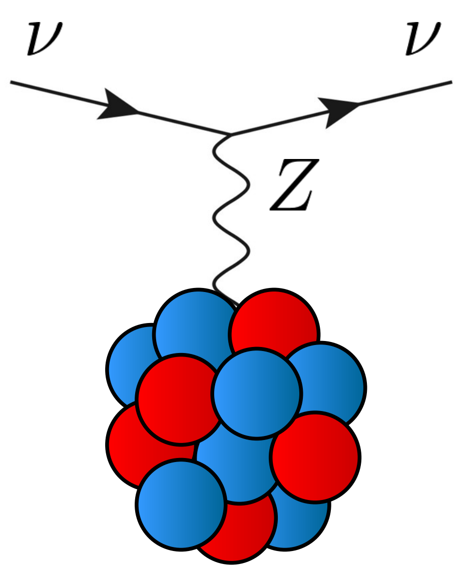


→ Shell model results from Hoferichter, Menendez, Schwenk, 2007.08529 (pheno parametrizations also exist, though)

Coherent neutrino-nucleus scattering

Hence, we need:

→ very low recoil energies, O(keV), since $q^2 \simeq 2ME_r$



Coherent neutrino-nucleus scattering

Hence, we need:

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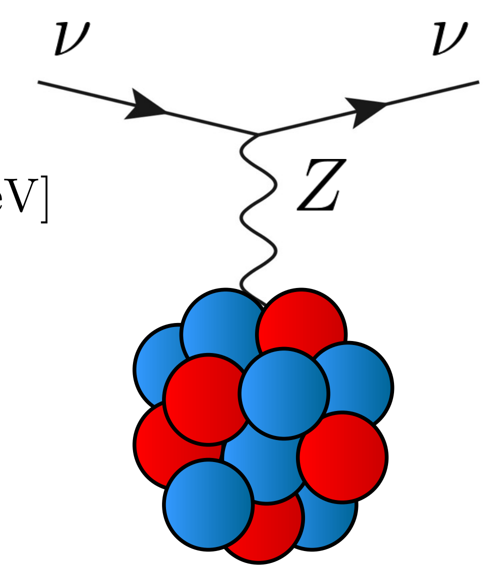
→ very low neutrino energies ($\lesssim$ 50 MeV) $\bar{E}_r = \frac{2}{3A}\left(\frac{E_\nu}{\text{MeV}}\right)^2$ [keV]

See e.g., Drukier & Stodolsky, PRD 30 (1984)



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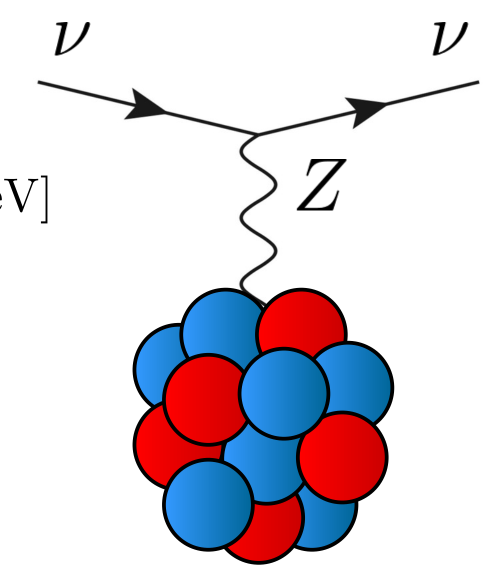
→ very intense sources



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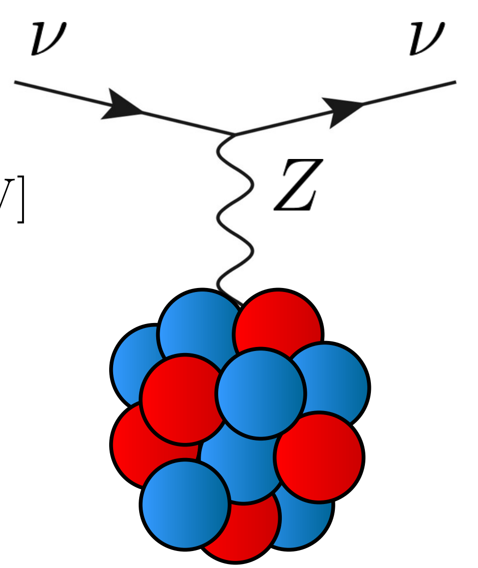


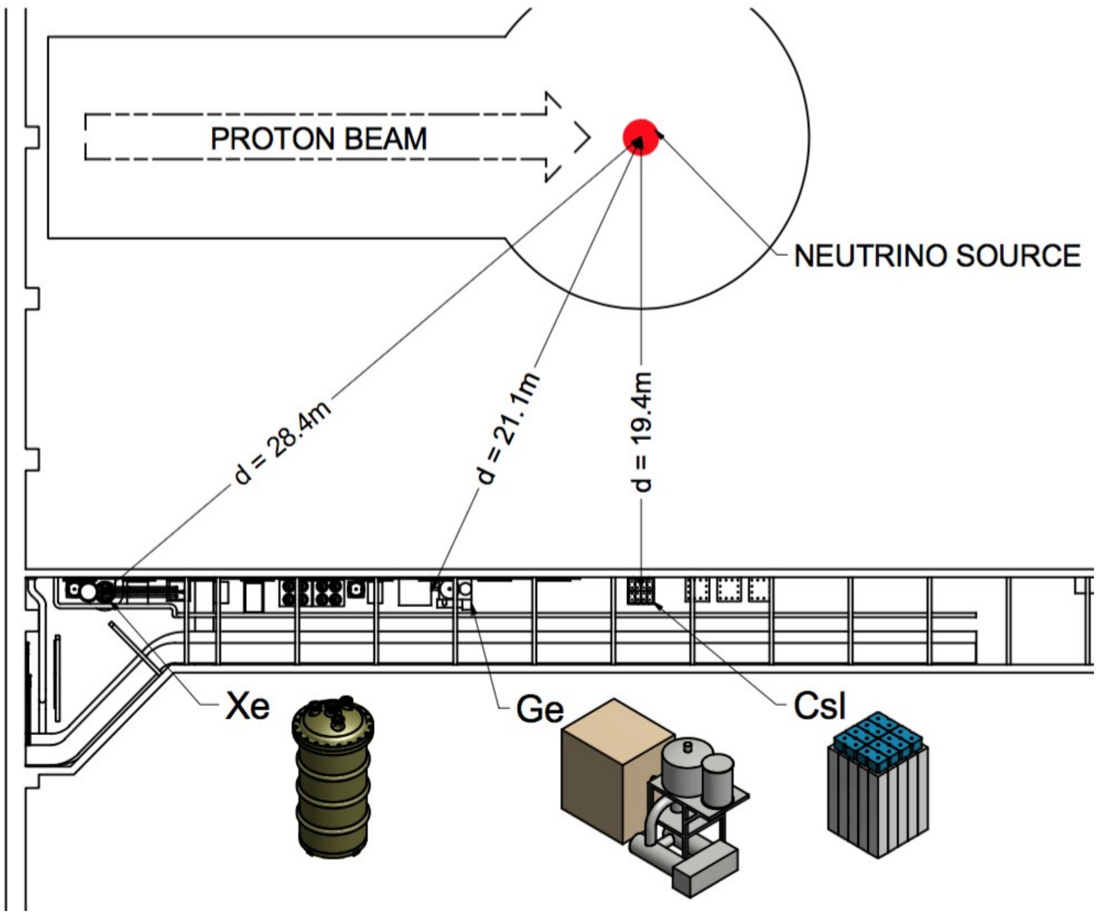
This boils down to:

- detectors very similar to those in direct detection experiments, but O(gr - kg) size

- lab neutrinos from reactors, spallation sources are ideal

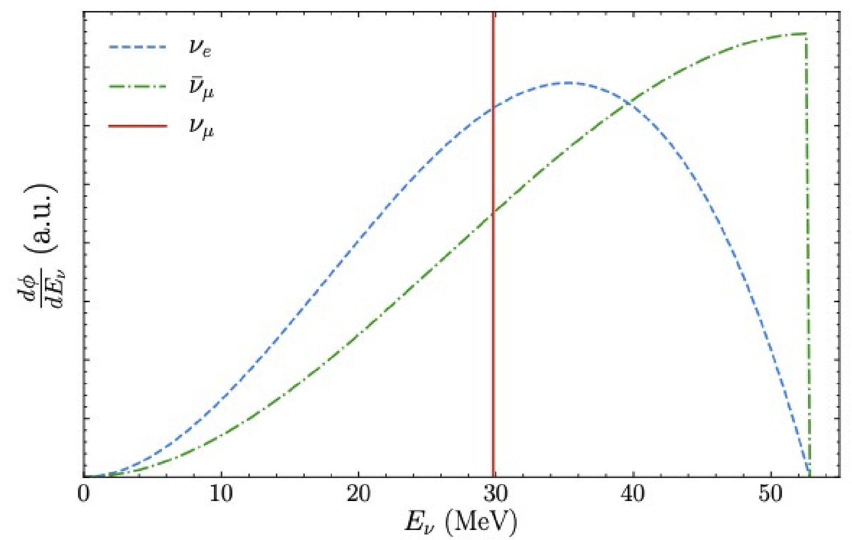
- detectors very close to the source (~ tens of meters), can be hosted on surface

Spallation sources: COHERENT



$$\pi^+ \to \mu^+ \nu_\mu$$

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$



COHERENT coll., 1509.08702

CEvNS searches at reactors

The much lower energy guarantees coherence condition is satisfied:

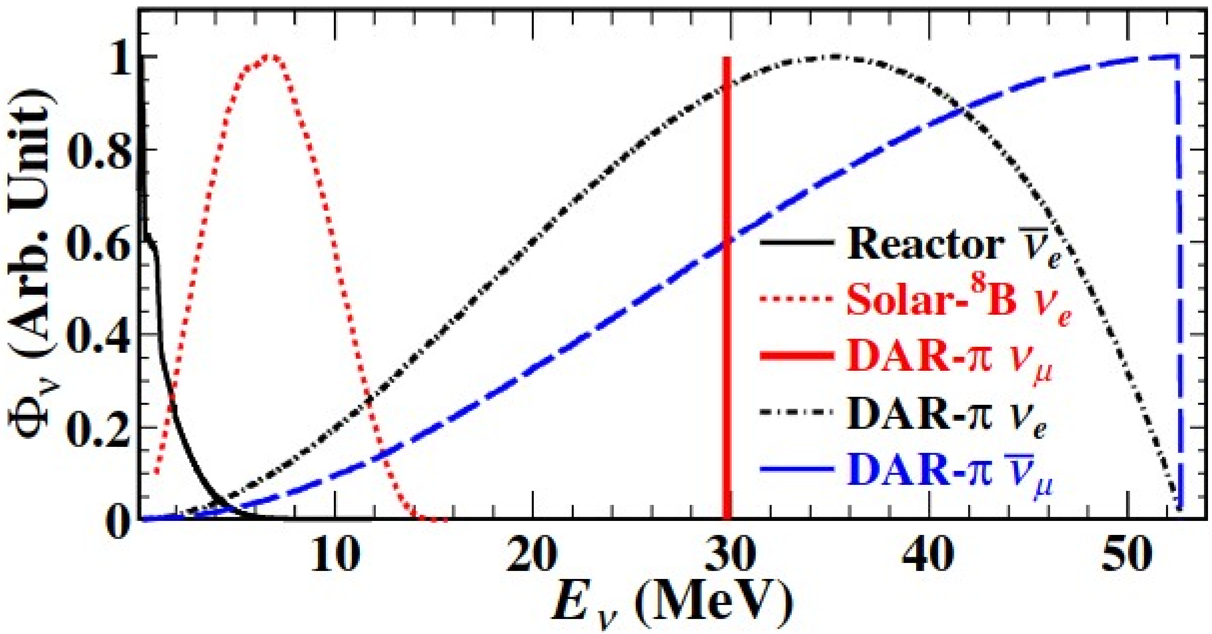
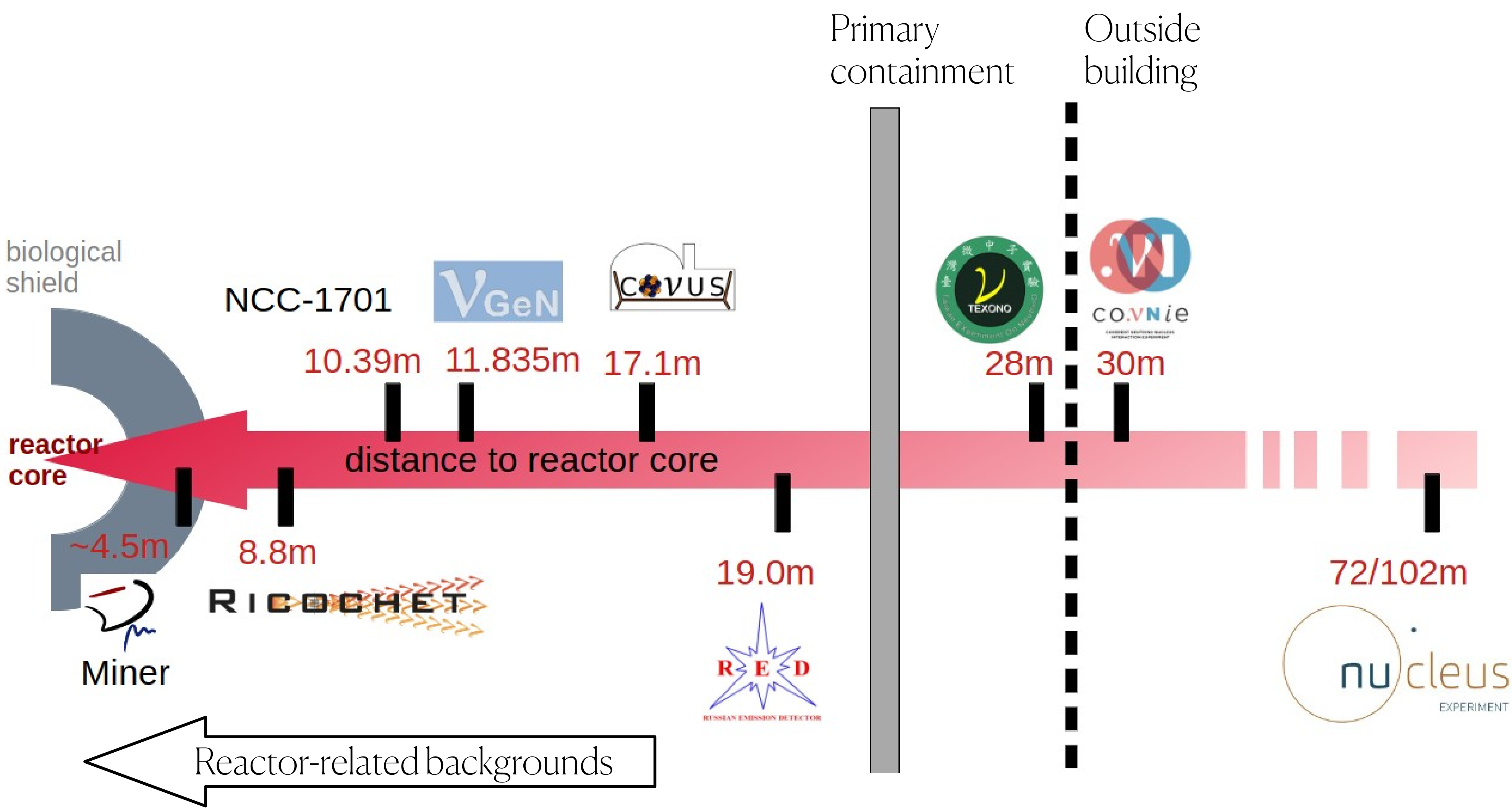


Figure from TEXONO coll., 2010.06810

CEvNS searches at reactors



Slide from J. Hakenmüller's talk at NDM22 symposium

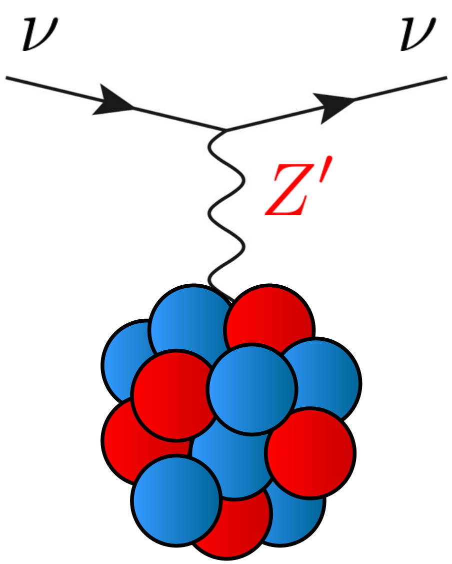
Coherent neutrino-nucleus scattering

In presence of vector NSI, neglecting oscillations:

$$\frac{d\sigma_\alpha}{dE_r} \simeq \frac{G_F^2}{2\pi}\frac{[\mathcal{Q}^2]_{\alpha\alpha}}{4} F_W^2(q^2) M \left(2 - \frac{M E_r}{E_\nu^2}\right)$$

$$[\mathcal{Q}]^2_{\alpha\alpha} = (\mathcal{Q}_{\alpha\alpha})^2 + \sum_{\beta\neq\alpha} |\mathcal{Q}_{\alpha\beta}|^2$$

$$\mathcal{Q}_{\alpha\beta}(\vec{\varepsilon}) = Z(g_p^V \delta_{\alpha\beta} + \varepsilon_{\alpha\beta}^{p,V}) + N(g_n^V \delta_{\alpha\beta} + \varepsilon_{\alpha\beta}^{n,V})$$



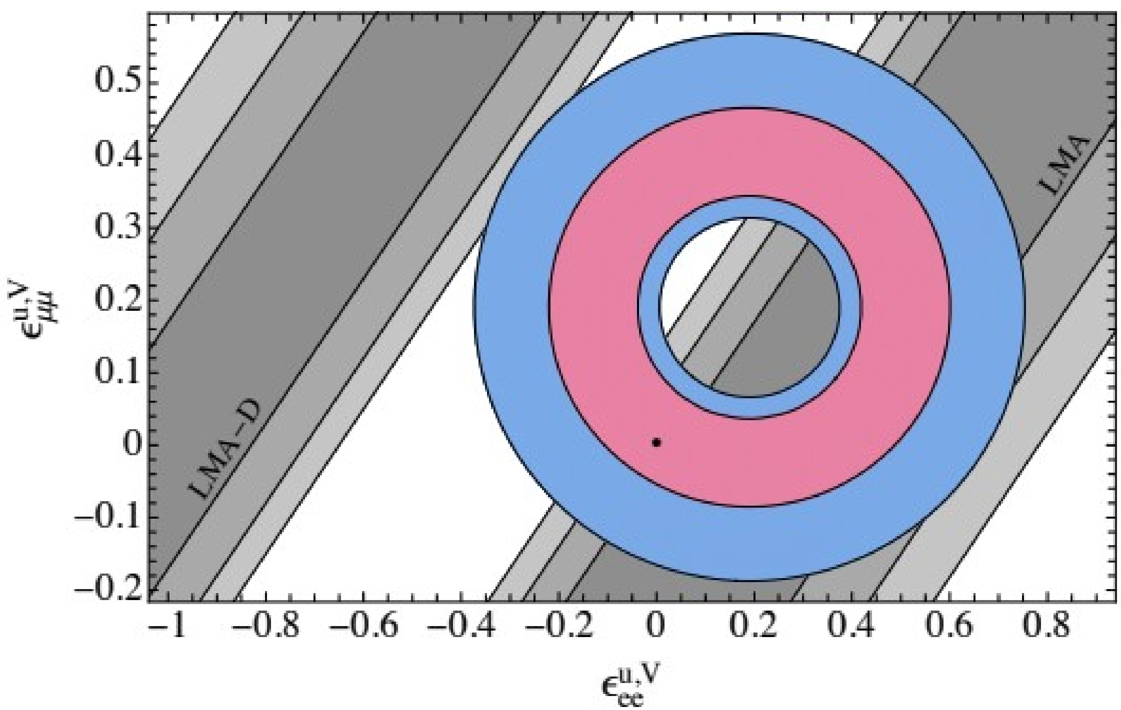
Take-home message:

- In presence of NSI, different charges allowed for different neutrino flavors
- The coherence condition → low q^2 → CEvNS falls in the contact interaction regime for a wide set of models with light mediators
- CEvNS is sensitive to the diagonal couplings separately → high complementarity with oscillation data

Spallation sources: COHERENT

$$N_{ev}^{\epsilon} = N_{ev}^{\rm SM} \quad \Rightarrow \quad \left[R + \epsilon_{ee}^{u,V}\right]^2 + 2\left[R + \epsilon_{\mu\mu}^{u,V}\right]^2 = 3R^2$$

From the CsI data alone



$$R \simeq \frac{g_n^V}{2Z/N + 1}$$

Coloma, Gonzalez-Garcia, Maltoni and Schwetz, 1708.02899

Coherent neutrino-nucleus scattering

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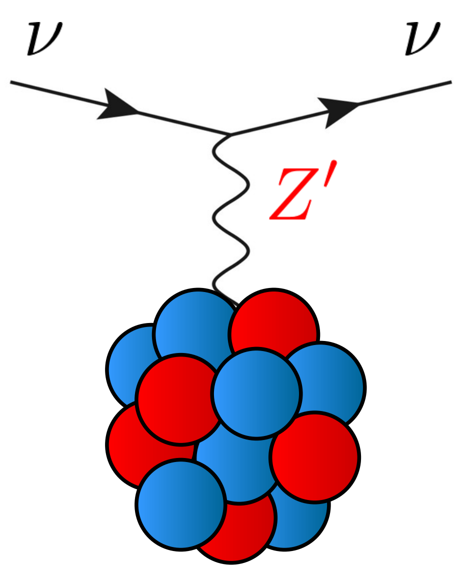

$$[\mathcal{Q}]^2_{\alpha\alpha} = (\mathcal{Q}_{\alpha\alpha})^2 + \sum_{\beta\neq\alpha} |\mathcal{Q}_{\alpha\beta}|^2$$

$$\mathcal{Q}_{\alpha\beta}(\vec{\varepsilon}) = Z(g_p^V \delta_{\alpha\beta} + \varepsilon_{\alpha\beta}^{p,V}) + N(g_n^V \delta_{\alpha\beta} + \varepsilon_{\alpha\beta}^{n,V})$$

Blind spot: for a given target, in full generality it is always possible to cancel the effect of NSI between protons and neutrons

→ Can be alleviated combining different data on different target materials

End of lecture II

Work supported by Grants RYC2018-024240-I, PID2019-108892RB-I00, CEX2020-001007-S, PID2022-142545NB-C21

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