Image credit: F. Fidani (ScienzaPerTutti)

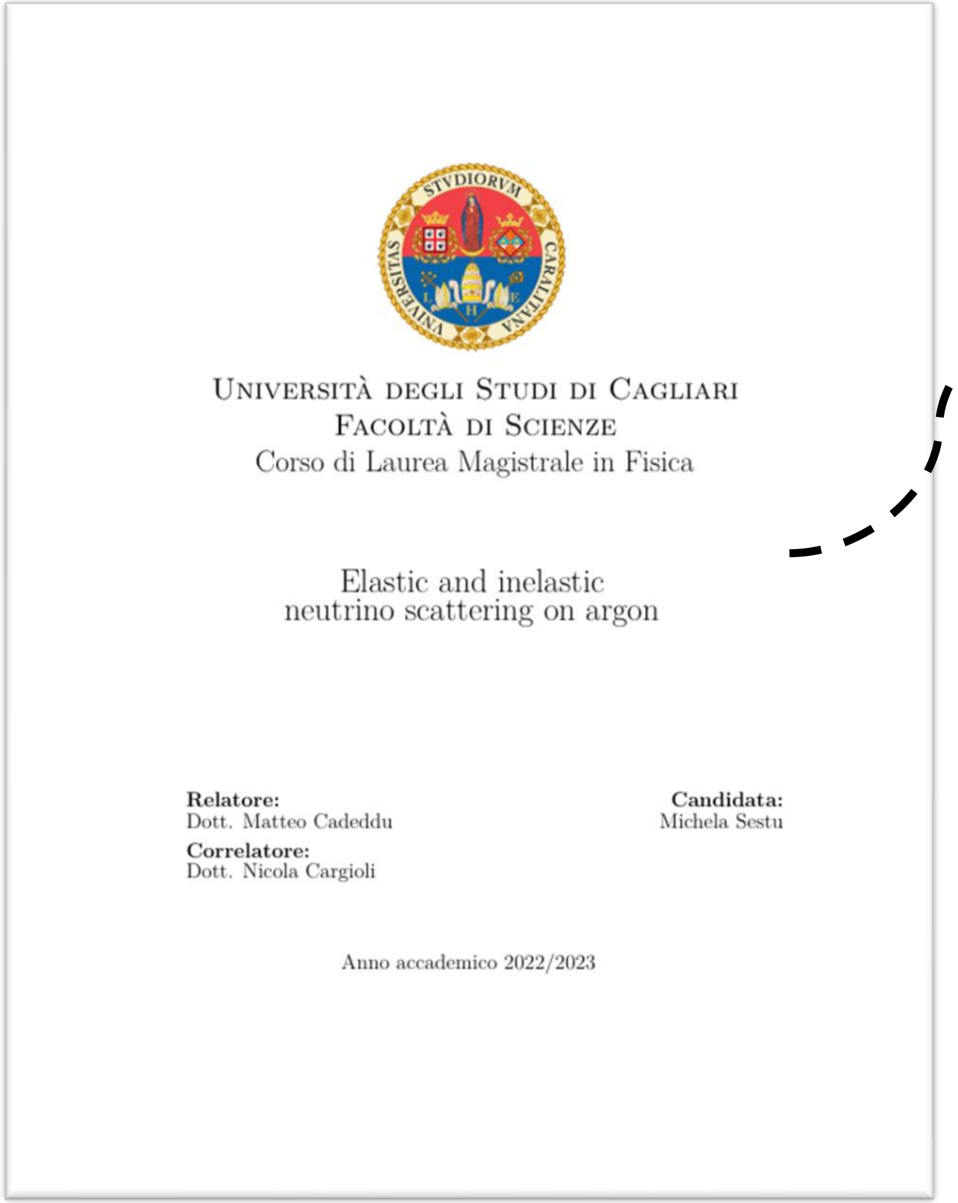
Women in Theoretical Physics

Premio Nazionale “Milla Baldo Ceolin" 2024

Michela Sestu
University of Cagliari & INFN Cagliari

Galileo Galilei Institute, Firenze
November 04, 2025

Master thesis: Elastic and inelastic neutrino scattering on argon

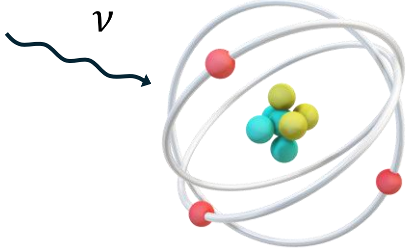

UNIVERSITÀ DEGLI STUDI DI CAGLIARI
FACOLTÀ DI SCIENZE
Corso di Laurea Magistrale in Fisica

Elastic and inelastic
neutrino scattering on argon

Relatore:
Dott. Matteo Cadeddu
Correlatore:
Dott. Nicola Cargioli

Candidata:
Michela Sestu

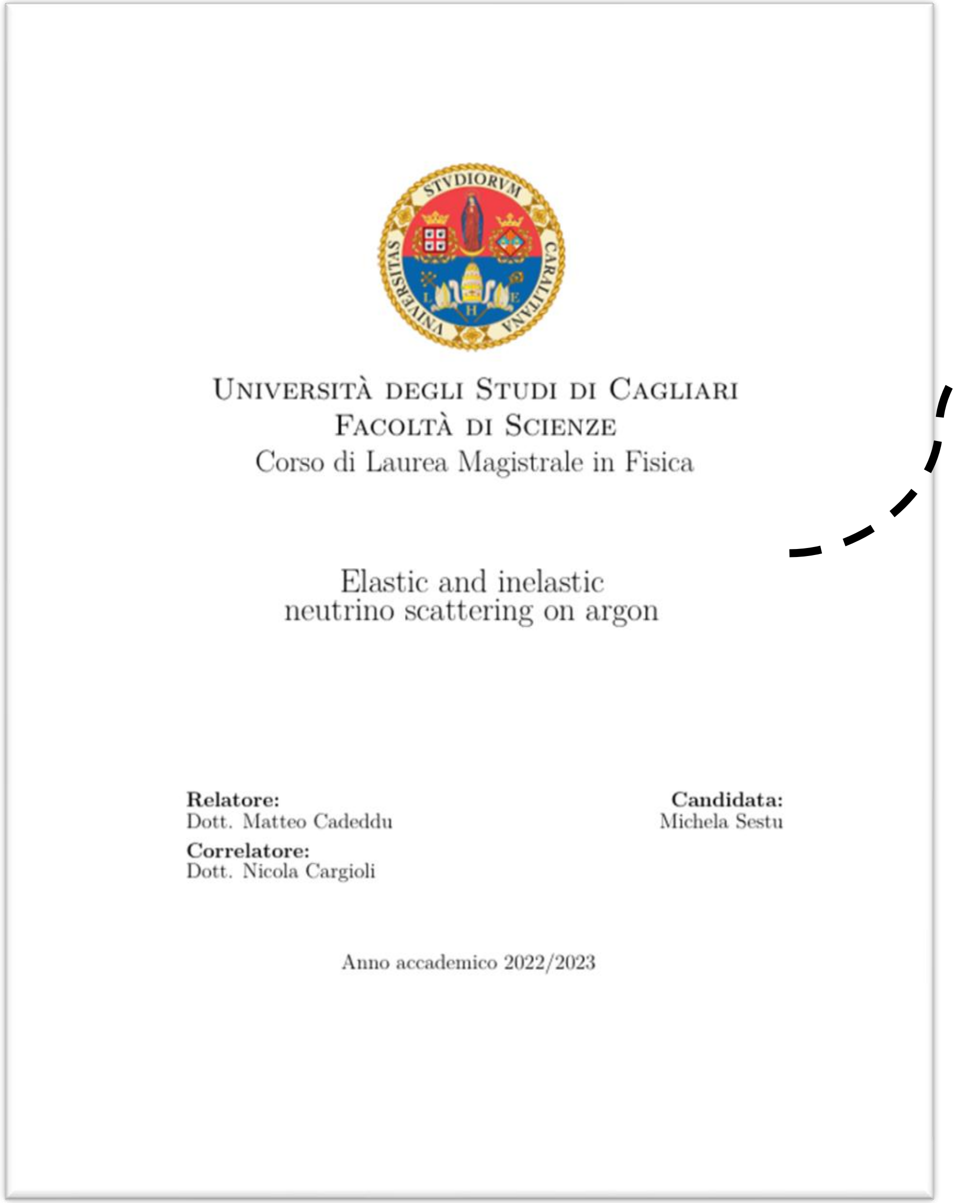
Anno accademico 2022/2023



Topic: neutrino interactions on $^{40}\mathrm{Ar}$
at **low energies** ($\lesssim$ 100 MeV)

Goal: precise calculation of **cross sections**

Master thesis: Elastic and inelastic neutrino scattering on argon

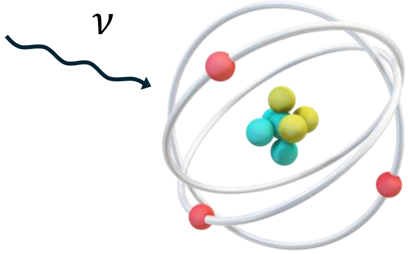

Università degli Studi di Cagliari
Facoltà di Scienze
Corso di Laurea Magistrale in Fisica

Elastic and inelastic
neutrino scattering on argon

Relatore:
Dott. Matteo Cadeddu
Correlatore:
Dott. Nicola Cargioli

Candidata:
Michela Sestu

Anno accademico 2022/2023



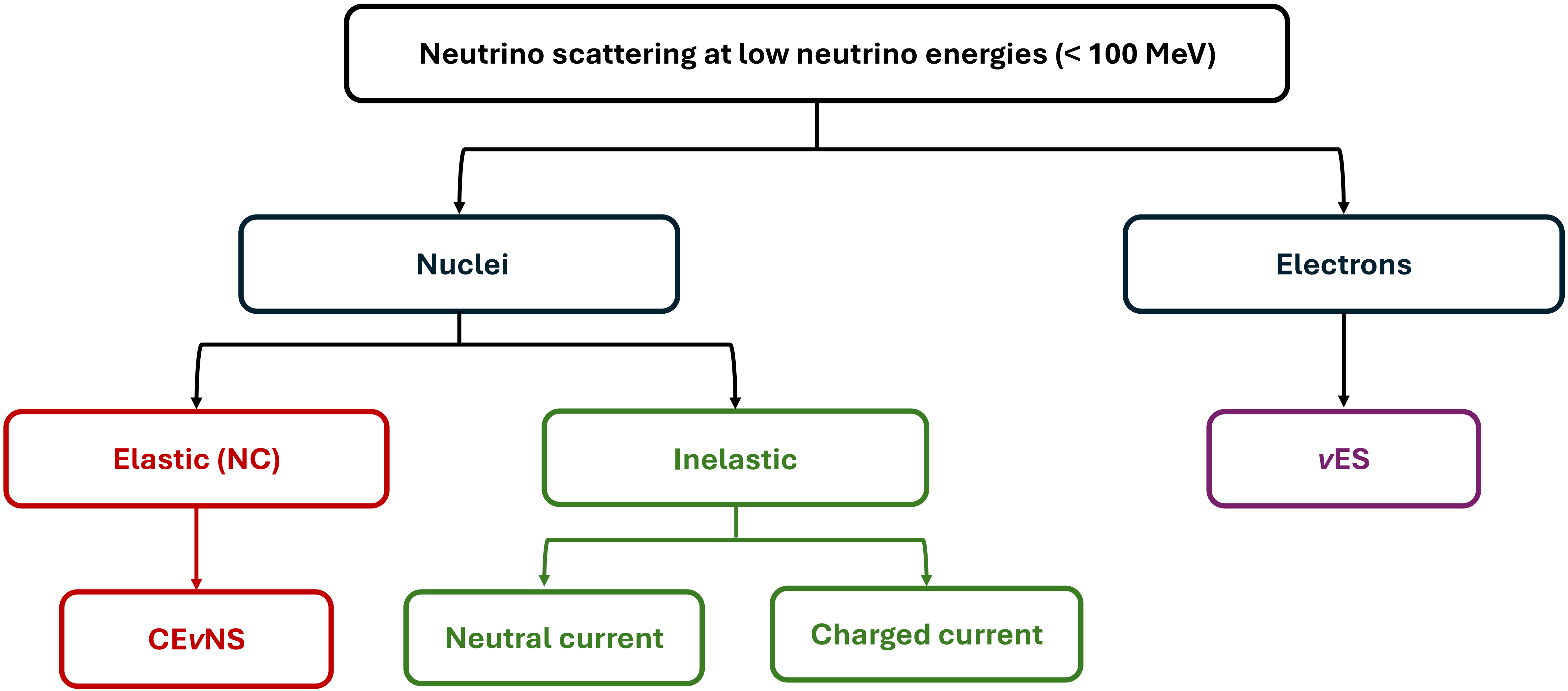
Topic: neutrino interactions on $^{40}\mathrm{Ar}$
at **low energies** ($\lesssim$ 100 MeV)

Goal: precise calculation of **cross sections**

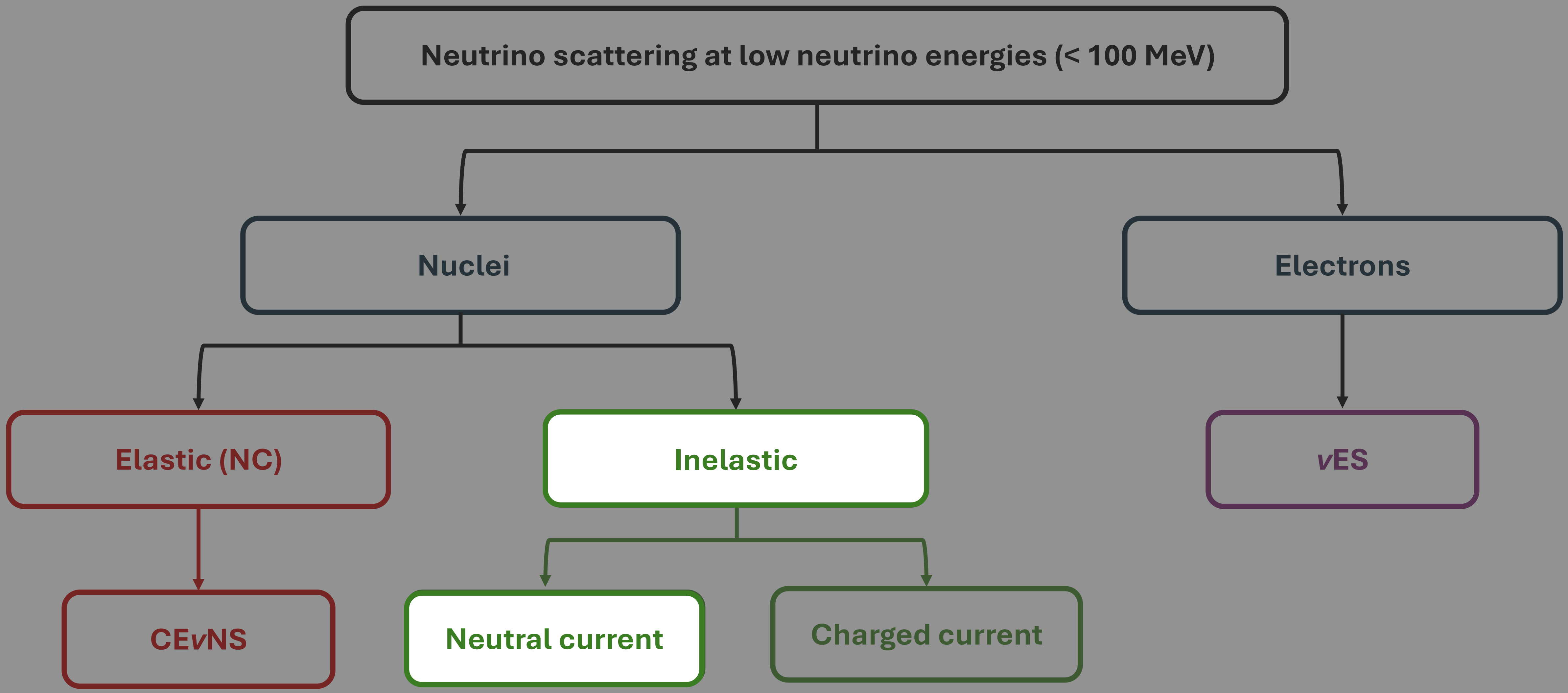
Why argon?

- Neutrino experiments (COHERENT, DUNE)
- Dark matter experiments (DarkSide-20k)
- Liquid Ar shield (LEGEND-1000)

Neutrino interactions



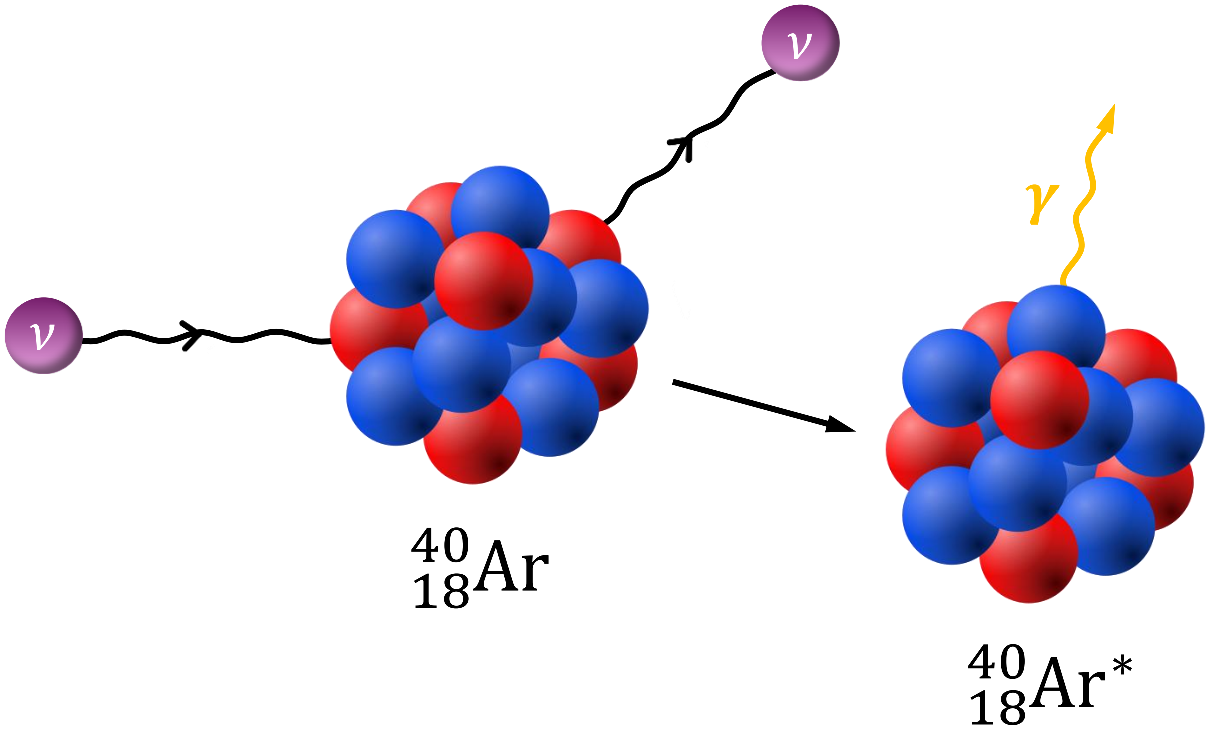
Neutrino interactions



Neutral current inelastic interaction

Neutral Current (NC)

$$\nu_e + {}^{40}_{18}\text{Ar} \longrightarrow \nu_e + {}^{40}_{18}\text{Ar}^*$$



Cross section recipe

Cross section recipe

1. Write the Hamiltonian: $\hat{H}_W = -\frac{G_F}{\sqrt{2}} \int d^3x \, j_\mu^{lept}(\mathbf{x}) \, \hat{\mathcal{J}}_\mu(\mathbf{x})$

Hadronic current

Leptonic current

Cross section recipe

1. Write the Hamiltonian: $$\hat{H}_W = -\frac{G_F}{\sqrt{2}}\int d^3x\; j_\mu^{lept}(\mathbf{x})\,\hat{\mathcal{J}}_\mu(\mathbf{x})$$

Hadronic current

Leptonic current

Cross section recipe

❶ Write the Hamiltonian: $\hat{H}_W = -\frac{G_F}{\sqrt{2}} \int d^3x \, j_\mu^{lept}(\mathbf{x}) \hat{\mathcal{J}}_\mu(\mathbf{x})$

Hadronic current

Leptonic current

❷ Expand the **hadronic current** into multipoles to obtain **many-body operators** acting on **nuclear states**

$$\hat{\mathcal{J}}_\mu = \hat{J}_\mu + \hat{J}_\mu^5 \longrightarrow \hat{\mathcal{M}}_{JM}(q) = \hat{M}_{JM} + \hat{M}_{JM}^5 = \int d^3x \, [j_J(qx) Y_{JM}(\Omega_x)] \, \hat{\mathcal{J}}_0(\mathbf{x})$$

V-A structure

Cross section recipe

1. Write the Hamiltonian: $$\hat{H}_W = -\frac{G_F}{\sqrt{2}} \int d^3x \, j_\mu^{lept}(\mathbf{x}) \hat{\mathcal{J}}_\mu(\mathbf{x})$$

Hadronic current

Leptonic current

2. Expand the **hadronic current** into multipoles to obtain **many-body operators** acting on **nuclear states**

$$\hat{\mathcal{J}}_\mu = \hat{J}_\mu + \hat{J}_\mu^5 \longrightarrow \hat{\mathcal{M}}_{JM}(q) = \hat{M}_{JM} + \hat{M}_{JM}^5 = \int d^3x \left[j_J(qx) Y_{JM}(\Omega_x) \right] \hat{\mathcal{J}}_0(\mathbf{x})$$

V-A structure

3. Express the **8 many-body operators** in terms of **7 one-body operators** acting on **sigle-nucleon states**

V

$$M_{JM} = F_1^N(q_\mu^2) M_J^M,$$
$$L_{JM} = \frac{q_0}{q} M_{JM},$$
$$T_{JM}^{\text{el}} = \frac{q}{m_n}\left(F_1^N(q_\mu^2)\Delta_J'^M + \frac{1}{2}\mu^N(q_\mu^2)\Sigma_J^M\right),$$
$$T_{JM}^{\text{mag}} = -\frac{iq}{m_n}\left(F_1^N(q_\mu^2)\Delta_J^M - \frac{1}{2}\mu^N(q_\mu^2)\Sigma_J'^M\right),$$

A

$$M_{JM}^5 = \frac{iq}{m_n}\left(G_A^N(q_\mu^2)\Omega_J'^M + \frac{1}{2} q_0 G_P^N(q_\mu^2)\Sigma_J''^M\right),$$
$$L_{JM}^5 = i\left(G_A^N(q_\mu^2) - \frac{q^2}{2m_n} G_P^N(q_\mu^2)\right)\Sigma_J''^M,$$
$$T_{JM}^{\text{el5}} = iG_A^N(q_\mu^2)\Sigma_J'^M,$$
$$T_{JM}^{\text{mag5}} = G_A^N(q_\mu^2)\Sigma_J^M,$$

B. Dutta et al., Phys. Rev. D 106, 113006 (2022)

Cross section recipe

1. Write the Hamiltonian: $$\hat{H}_W = -\frac{G_F}{\sqrt{2}}\int d^3x\, j_\mu^{lept}(\mathbf{x})\,\hat{\mathcal{J}}_\mu(\mathbf{x})$$

Hadronic current

Leptonic current

2. Expand the **hadronic current** into multipoles to obtain **many-body operators** acting on **nuclear states**

$$\hat{\mathcal{J}}_\mu = \hat{J}_\mu + \hat{J}^5_\mu \longrightarrow \hat{\mathcal{M}}_{JM}(q) = \hat{M}_{JM} + \hat{M}^5_{JM} = \int d^3x\,[j_J(qx)Y_{JM}(\Omega_x)]\,\hat{\mathcal{J}}_0(\mathbf{x})$$

V-A structure

3. Express the 8 many-body operators in terms of **7 one-body operators** acting on **sigle-nucleon states**

V

$$M_{JM} = F_1^N(q_\mu^2)\,M_J^M,$$
$$L_{JM} = \frac{q_0}{q}M_{JM},$$
$$T^{\text{el}}_{JM} = \frac{q}{m_n}\left(F_1^N(q_\mu^2)\,\Delta_J'^M + \frac{1}{2}\mu^N(q_\mu^2)\,\Sigma_J^M\right),$$
$$T^{\text{mag}}_{JM} = -\frac{iq}{m_n}\left(F_1^N(q_\mu^2)\,\Delta_J^M - \frac{1}{2}\mu^N(q_\mu^2)\,\Sigma_J'^M\right),$$

A

$$M^5_{JM} = \frac{iq}{m_n}\left(G_A^N(q_\mu^2)\,\Omega_J'^M + \frac{1}{2}q_0 G_P^N(q_\mu^2)\,\Sigma_J''^M\right),$$
$$L^5_{JM} = i\left(G_A^N(q_\mu^2) - \frac{q^2}{2m_n}G_P^N(q_\mu^2)\right)\Sigma_J''^M$$
$$T^{\text{el5}}_{JM} = iG_A^N(q_\mu^2)\,\Sigma_J'^M,$$
$$T^{\text{mag5}}_{JM} = G_A^N(q_\mu^2)\,\Sigma_J^M,$$

B. Dutta et al., Phys. Rev. D 106, 113006 (2022)

Inelastic NC cross section

Total differential cross section

$$\left(\frac{d\sigma}{d\Omega}\right)_{\nu,\bar{\nu}} = \frac{2G_F^2}{\pi\,(2J_i+1)} E_f^2 \cos^2\frac{\theta}{2} \Bigg\{ \sum_{J=0}^{\infty} \left| \left\langle J_f \left\| \hat{\mathcal{M}}_J + \frac{q_0}{q}\hat{\mathcal{L}}_J \right\| J_i \right\rangle \right|^2$$
$$+ \left[-\frac{q_\mu^2}{2q^2} + \tan^2\frac{\theta}{2}\right] \sum_{J=1}^{\infty} \left[|\langle J_f \| \hat{\mathcal{T}}_J^{\mathrm{el}} \| J_i \rangle|^2 + |\langle J_f \| \hat{\mathcal{T}}_J^{\mathrm{mag}} \| J_i \rangle|^2 \right]$$
$$\mp 2\tan\frac{\theta}{2} \left[-\frac{q_\mu^2}{q^2} + \tan^2\frac{\theta}{2}\right]^{1/2} \sum_{J=1}^{\infty} \mathrm{Re}\left(\langle J_f \| \hat{\mathcal{T}}_J^{\mathrm{mag}} \| J_i \rangle \langle J_f \| \hat{\mathcal{T}}_J^{\mathrm{el}} \| J_i \rangle^* \right) \Bigg\}$$

Inelastic NC cross section

Total differential cross section

$$\left(\frac{d\sigma}{d\Omega}\right)_{\nu,\bar{\nu}} = \frac{2G_F^2}{\pi(2J_i+1)} E_f^2 \cos^2\frac{\theta}{2} \left\{ \sum_{J=0}^{\infty} \left| \left\langle J_f \left\| \hat{\mathcal{M}}_J + \frac{q_0}{q}\hat{\mathcal{L}}_J \right\| J_i \right\rangle \right|^2 \right.$$
$$+ \left[-\frac{q_\mu^2}{2q^2} + \tan^2\frac{\theta}{2} \right] \sum_{J=1}^{\infty} \left[\left| \langle J_f \| \hat{\mathcal{T}}_J^{\mathrm{el}} \| J_i \rangle \right|^2 + \left| \langle J_f \| \hat{\mathcal{T}}_J^{\mathrm{mag}} \| J_i \rangle \right|^2 \right]$$
$$\left. \mp 2\tan\frac{\theta}{2} \left[-\frac{q_\mu^2}{q^2} + \tan^2\frac{\theta}{2} \right]^{1/2} \sum_{J=1}^{\infty} \mathrm{Re}\left(\langle J_f \| \hat{\mathcal{T}}_J^{\mathrm{mag}} \| J_i \rangle \langle J_f \| \hat{\mathcal{T}}_J^{\mathrm{el}} \| J_i \rangle^* \right) \right\}$$

Are we done?

Inelastic NC cross section… at low energies

$E_\nu \lesssim 100$ MeV

Inelastic NC cross section… at low energies

$$\sigma_{GT}^{(NC)} \backsimeq \frac{G_F^2\, g_A^2}{\pi} (\boldsymbol{E_\nu} - \Delta E)^2 \left| \left\langle J_f \left\| \sum_{i=1}^{A} \tau_\pm(i) \sigma_{1M}(i) \right\| J_i \right\rangle \right|^2$$

Nuclear excitation energy

$\lesssim$ 100 MeV

$B(GT)$

Gamow-Teller transition probabilities

No direct experimental measurements
No reliable theoretical predictions

Estimation of nuclear matrix elements

1 Theoretical approach

Transition probabilities are computed through BIGSTICK, a **nuclear shell model** code.

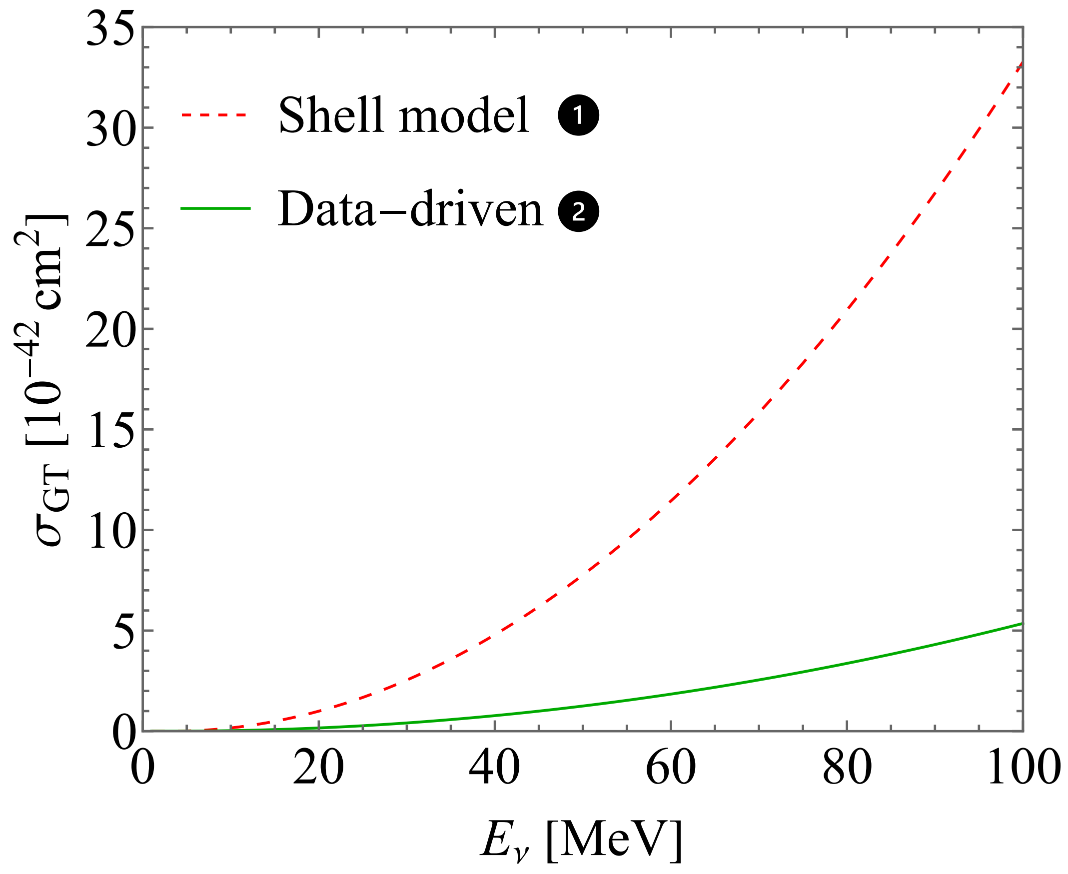
2 Data-driven approach

We consider **experimental measurements** of the magnetic dipole amplitudes B(M1) for the process:

$$\gamma + {}^{40}_{18}\mathrm{Ar} \longrightarrow \gamma + {}^{40}_{18}\mathrm{Ar}$$

At low energies: $B(GT)^{exp} = \frac{B(M1)}{g_A^2(2.2993\,\mu_N)^2}$

W. Tornov et al., Phys. Lett. B 835 (2022)



Estimation of nuclear matrix elements

1 **Theoretical approach**

Transition probabilities are computed through BIGSTICK, a **nuclear shell model** code.

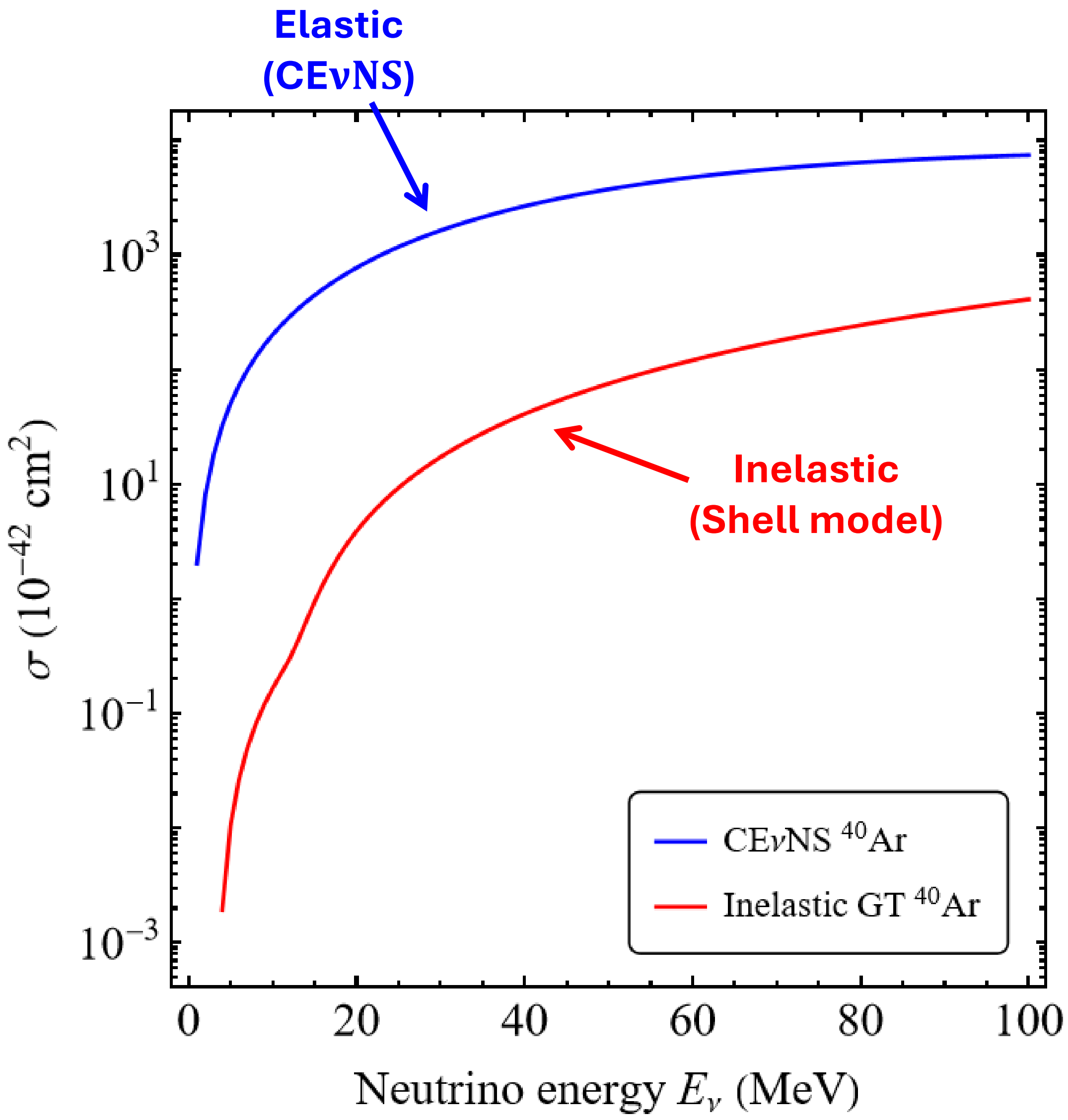
2 **Data-driven approach**

We consider **experimental measurements** of the magnetic dipole amplitudes B(M1) for the process:

$$\gamma + {}^{40}_{18}\mathrm{Ar} \longrightarrow \gamma + {}^{40}_{18}\mathrm{Ar}$$

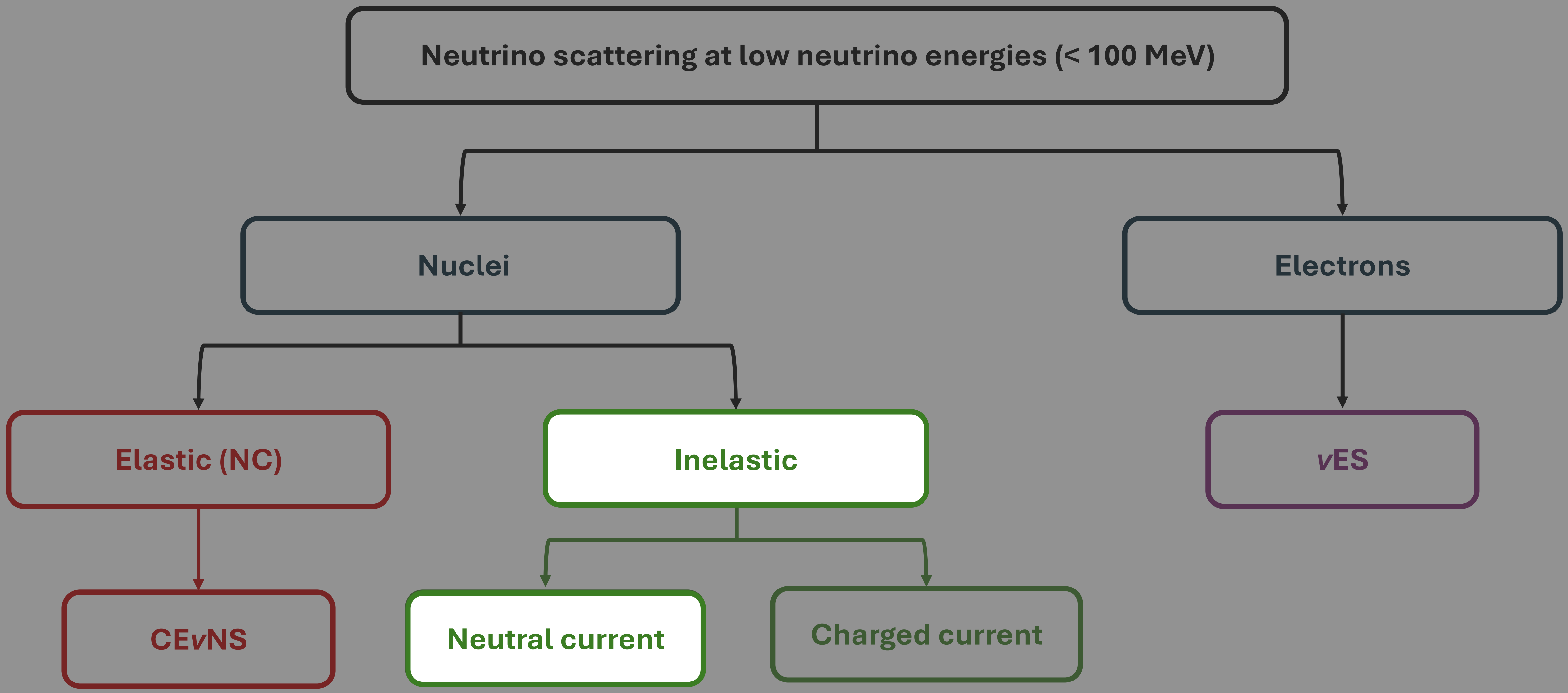
At low energies: $B(GT)^{exp} = \frac{B(M1)}{g_A^2(2.2993\ \mu_N)^2}$

W. Tornov et al., Phys. Lett. B 835 (2022)

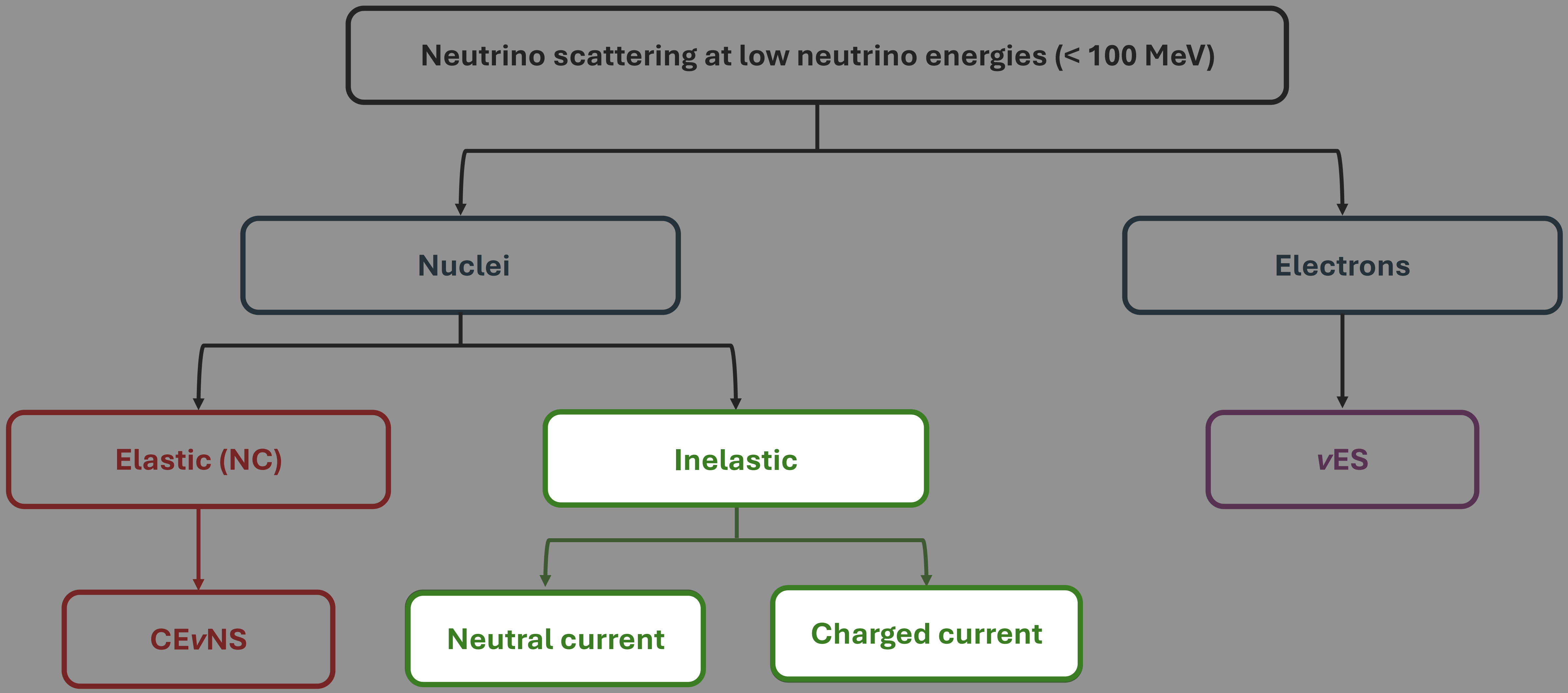


What’s next?
My PhD so far

Neutrino interactions

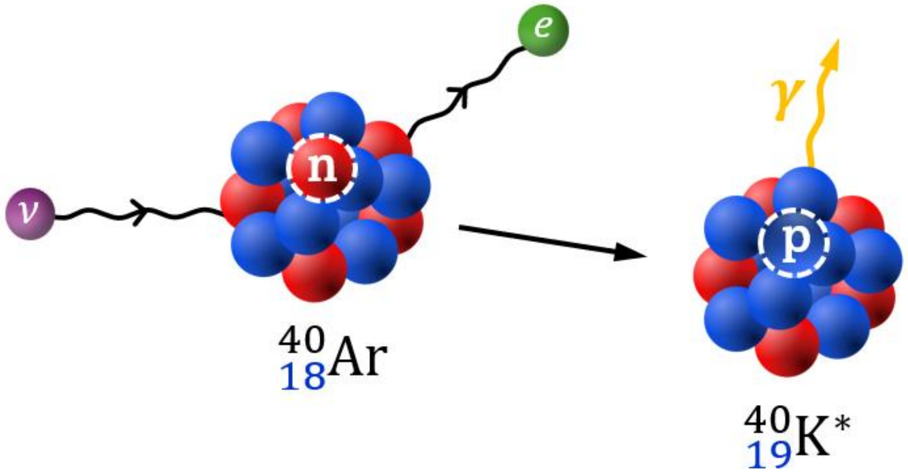


Neutrino interactions



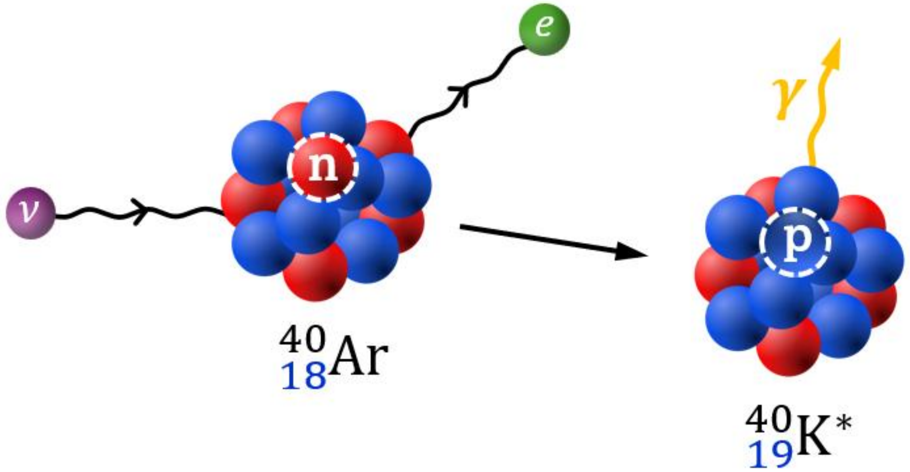
Charged current inelastic interaction

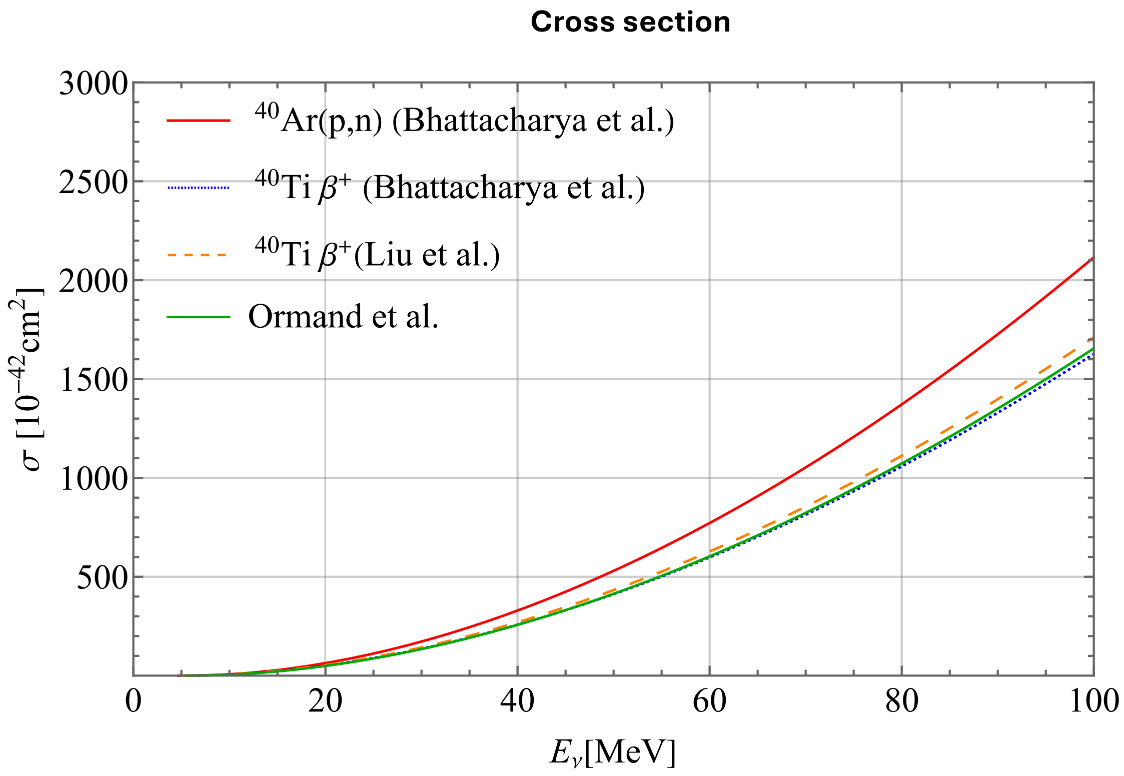
$$\nu_e + {}^{40}_{18}\text{Ar} \longrightarrow e^- + {}^{40}_{19}\text{K}^*$$



Charged current inelastic interaction

$$\nu_e + {}^{40}_{18}\mathrm{Ar} \longrightarrow e^- + {}^{40}_{19}\mathrm{K}^*$$

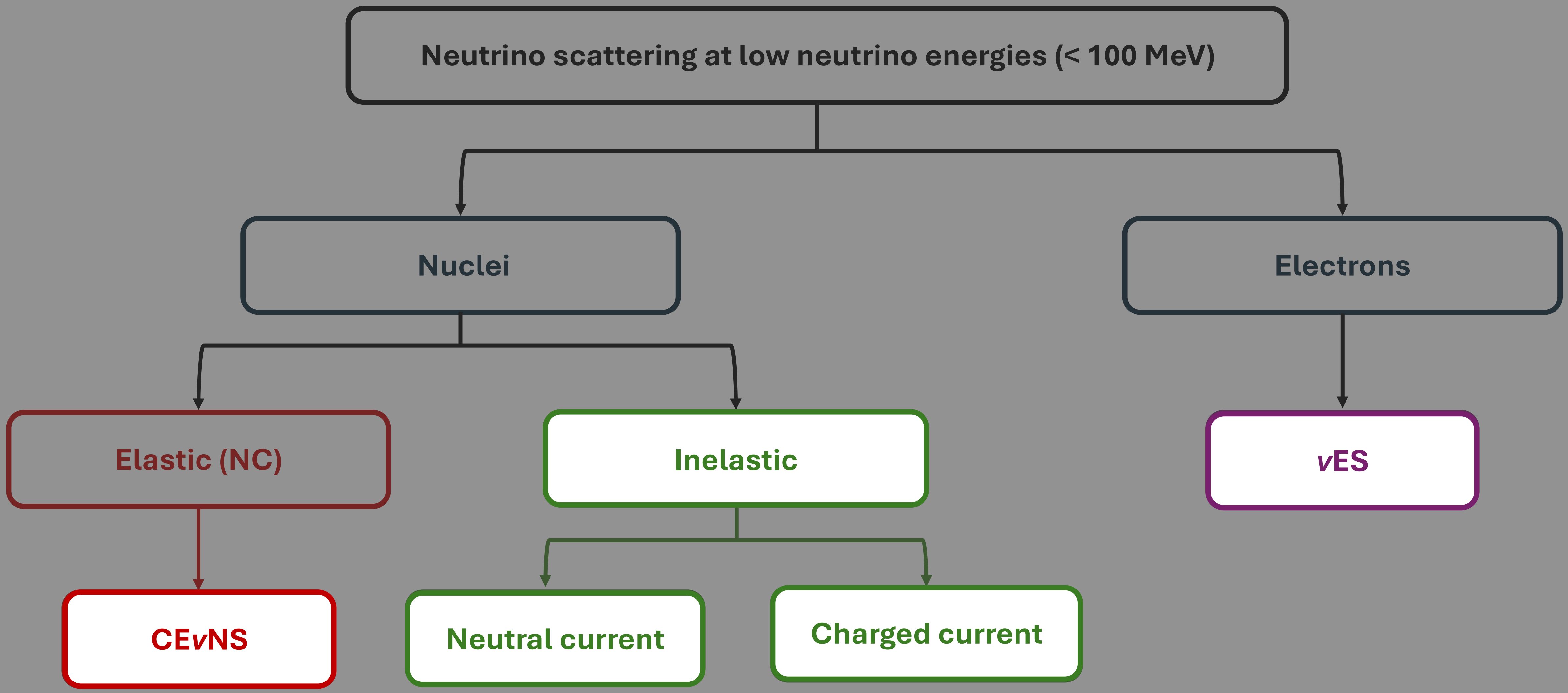




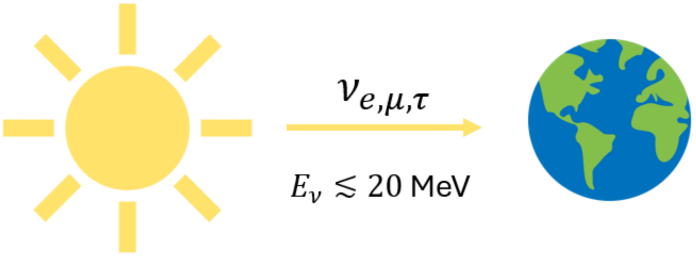
$$\sigma^{(CC)}_{GT+F} = \sum_i \frac{G_F^2 |V_{ud}|^2}{\pi} |\mathcal{M}_{o\to i}|^2 E_e^i\, p_e^i F(Z, E_e^i)$$

Fermi function

Neutrino interactions

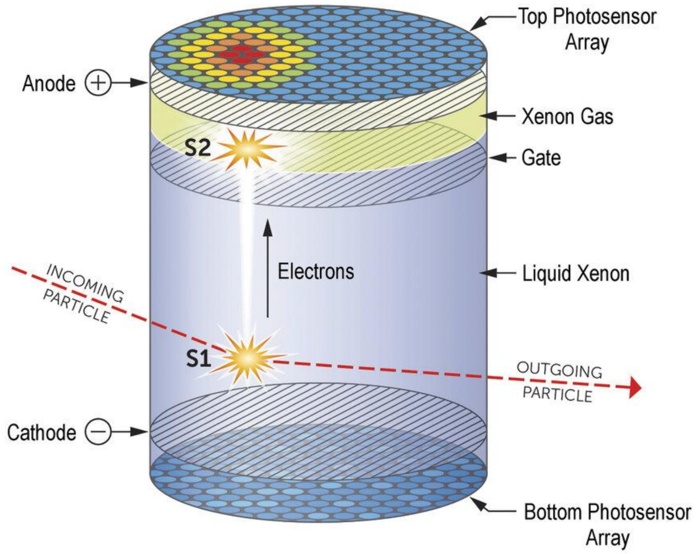


Solar neutrinos



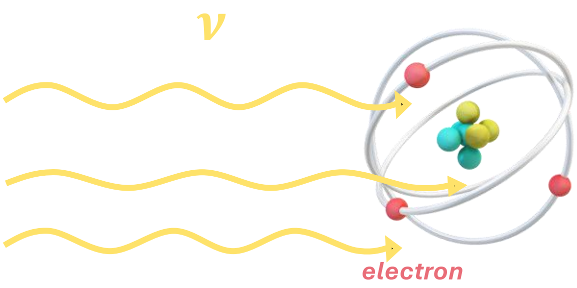
→

Neutrinos constitute a background at direct detection **dark matter experiments**



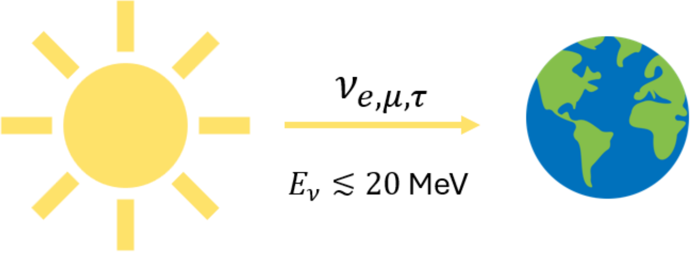
←

Elastic interactions of neutrinos with **electrons** and **nuclei**

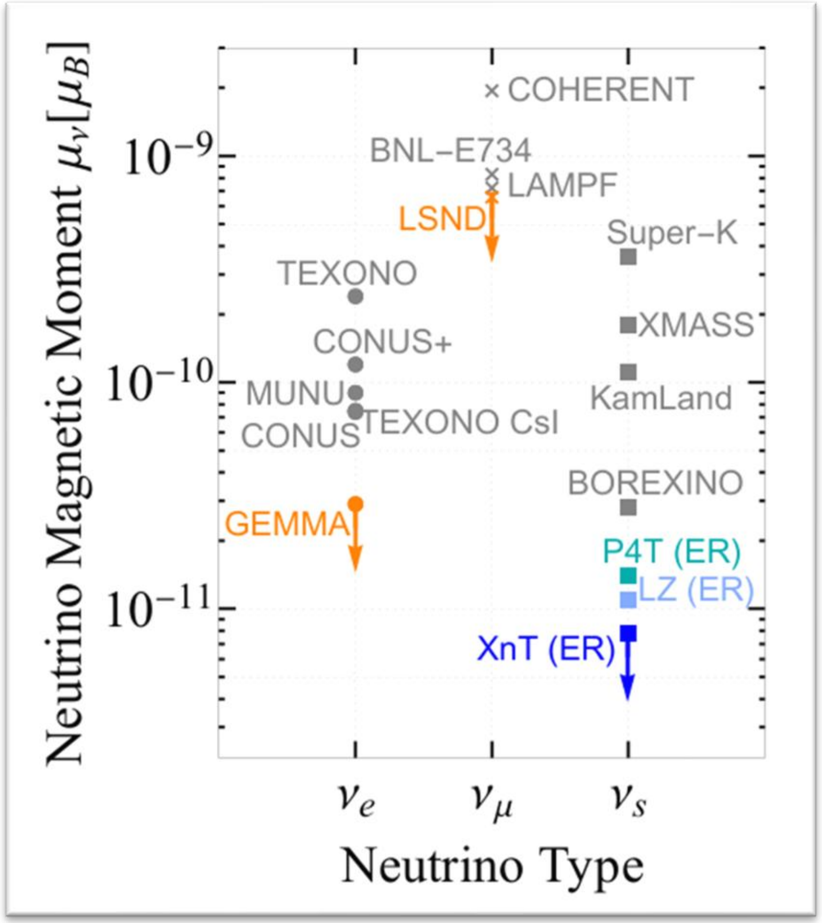


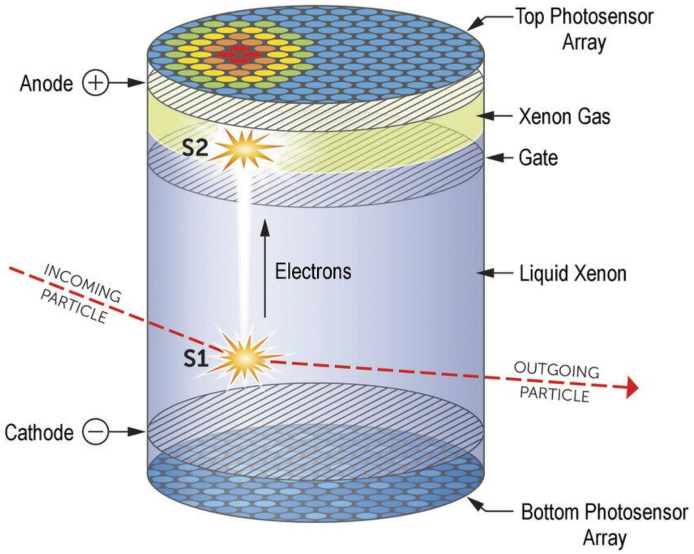
M. Sestu et al., Arxiv: 2509.22178

Solar neutrinos



Neutrinos constitute a background at direct detection **dark matter experiments**





M. Sestu et al., Arxiv: 2509.22178

Thank you for your attention!