CEνNS nuclear physics aspects

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Outline

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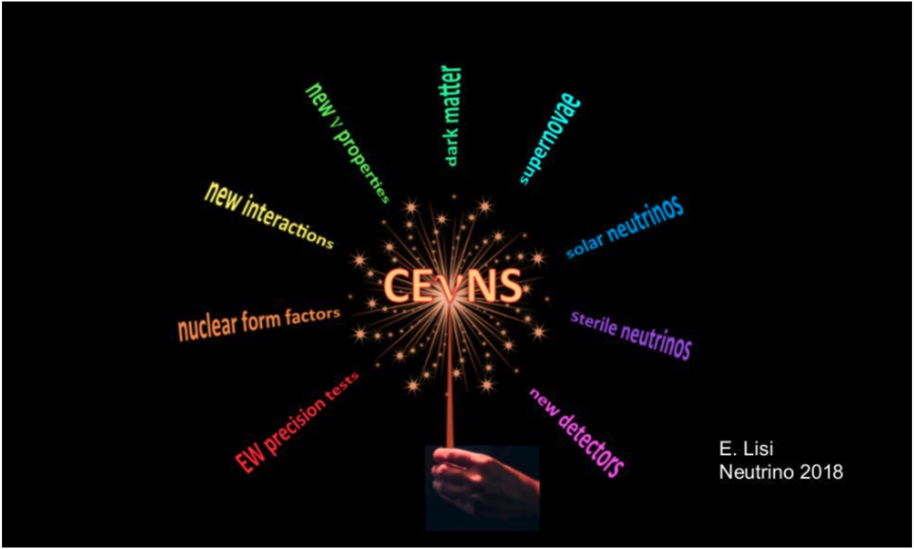
   - Experimental status and motivations of CEνNS
2. CEvNS in the Standard Model
   - Reactor, accelerator and astrophysical-induced event rates
   - Impact of nuclear form factors
   - Beyond CEvNS: Incoherent calculations
3. Electromagnetic neutrino properties
   - Neutrino magnetic moments & charge radii
   - Active-sterile transitions
4. Summary

Physics Motivations of CEνNS



talks by O. Miranda, N. Cargioli

CEνNS experiments worldwide

slide from Carla Bonifazi: TAUP 2021, Valencia

talks by Scholberg (COHERENT), Hakenmüller (CONUS)

Standard Model physics & nuclear structure

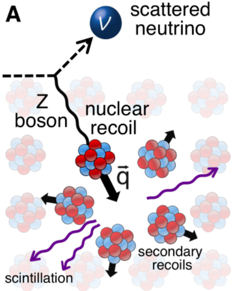
Standard Model CEνNS cross section

CEνNS cross section expressed through the nuclear recoil energy T_A

$$\left(\frac{d\sigma}{dT_A}\right)_{SM} = \frac{G_F^2 m_A}{\pi}\left[\mathcal{Q}_V^2\left(1-\frac{m_A T_A}{2E_\nu^2}\right)+\mathcal{Q}_A^2\left(1+\frac{m_A T_A}{2E_\nu^2}\right)\right]F^2(Q^2)$$

[DKP, Kosmas: PRD 97 (2018)]

- E_ν: is the incident neutrino energy
- m_A: the nuclear mass of the detector material
- Z protons and $N = A - Z$ neutrons
- vector $\mathcal{Q}_V$ and axial vector $\mathcal{Q}_A$ contributions
- $F(Q^2)$: is the nuclear form factor



$$\mathcal{Q}_V = \left[2(g_u^L+g_u^R)+(g_d^L+g_d^R)\right]Z+\left[(g_u^L+g_u^R)+2(g_d^L+g_d^R)\right]N\,,$$

$$\mathcal{Q}_A = \left[2(g_u^L-g_u^R)+(g_d^L-g_d^R)\right](\delta Z)+\left[(g_u^L-g_u^R)+2(g_d^L-g_d^R)\right](\delta N)\,,$$

- $(\delta Z) = Z_+ - Z_-$ and $(\delta N) = N_+ - N_-$, where Z_+ (N_+) and Z_- (N_-) refers to total number of protons (neutrons) with spin up or down [Barranco et al.: JHEP 0512 (2005)]

Standard Model CEνNS cross section

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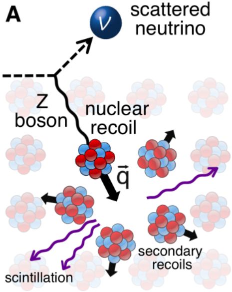
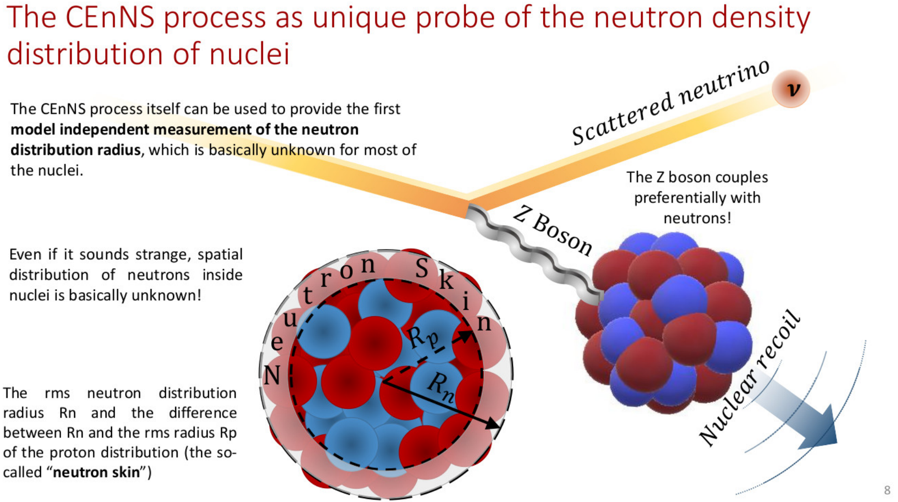


$$\mathcal{Q}_V = \left[\frac{1}{2} - 2\sin^2\theta_W\right] Z - \frac{1}{2}N\,,$$
$$\mathcal{Q}_A = \frac{1}{2}(\delta Z) + \frac{1}{2}(\delta N)\,,$$

- weak mixing angle: $\sin^2\theta_W$ not well measured at low energies

Nuclear rms radius

Phenomenological studies: form factor written in terms of the rms radius



slide from: M. Cadeddu @ NuFact 2018

Phenomenological form factors (Klein-Nystrand)

Follows from the convolution of a Yukawa potential with range $a_k = 0.7$ fm over a Woods-Saxon distribution, approximated as a hard sphere with radius R_A.

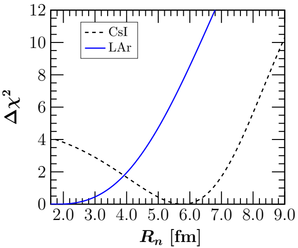
$$F_{\text{KN}} = 3\frac{j_1(QR_A)}{qR_A}\left[1 + (Qa_k)^2\right]^{-1}$$

The rms radius is: $\langle R^2 \rangle_{\text{KN}} = 3/5 R_A^2 + 6a_k^2$

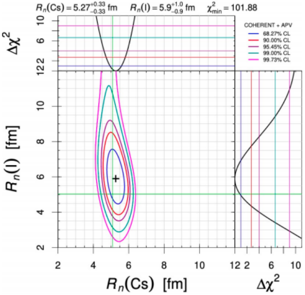
[Klein, Nystrand, PRC 60 (1999) 014903]

- **CEvNS data provides:** a data driven determination of the neutron rms radius
- **COHERENT (CsI) + APV (Cs):** can disentangle the Cs and I contributions

[Miranda et al. JHEP 05 (2020) 130]



[Cadeddu et al., arXiv:2102.06153]



talk by N. Cargioli

Nuclear structure models: BCS calculations

Within the context of the quasi-particle random phase approximation (QRPA) method, the form factors for protons (neutrons) are obtained as

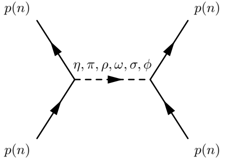
$$F_{N_n} = \frac{1}{N_n} \sum_j \hat{j} \langle g.s. || j_0(|\mathbf{q}|r) || g.s. \rangle \left(v_j^{p(n)} \right)^2$$

where $\hat{j} = \sqrt{2j+1}$, $N_n = Z$ (or N), $v_j^{p(n)}$ are the BCS probability amplitudes, determined by solving iteratively the BCS equations.

[Kosmas, Vergados, Civitarese, Faessler, NPA 570 (1994) 637]

After choosing the active model space the following important parameters must be properly adjusted

- the harmonic oscillator (h.o.) size parameter b
- the two pairing parameters $g_{\rm pair}^{p\,(n)}$ for proton (neutron) pairs that renormalise the monopole (pairing) residual interaction of the Bonn C-D two-body potential (describing the strong two-nucleon forces)



- *Realistic proton and neutron form factors*
- The Bonn C-D residual interaction is mediated via one-meson exchange
  [Machleidt, PRC 63 (2001) 024001]

Nuclear structure models: deformed shell model

Kota & Sahu: *Structure of Medium Mass Nuclei: Deformed Shell Model and Spin-Isospin Interacting Boson Model*, CRC Press

- **Assume axial symmetry**
- **Model space**: a set single-particle (sp) orbitals + an effective two-body Hamiltonian
- **Lowest-energy intrinsic states**: by solving the HF single-particle equation self-consistently.
- **Excited intrinsic configurations**: via particle-hole excitations over the lowest intrinsic state.
- **Problem!** Intrinsic states $\chi_K(\eta)$: do not have definite angular momenta

States of good angular momentum, projected from an intrinsic state $\chi_K(\eta)$

$$|\psi^J_{MK}(\eta)\rangle = \frac{2J+1}{8\pi^2\sqrt{N_{JK}}} \int d\Omega D^{J^*}_{MK}(\Omega) R(\Omega) |\chi_K(\eta)\rangle ,$$

where N_{JK} is the normalization constant given by

$$N_{JK} = \frac{2J+1}{2} \int_0^\pi d\beta \sin\beta d^J_{KK}(\beta) \langle \chi_K(\eta)| e^{-i\beta J_y} |\chi_K(\eta)\rangle .$$

- $R(\Omega) = \exp(-i\alpha J_z)\exp(-i\beta J_y)\exp(-i\gamma J_z)$: general rotation operator
- Ω: the Euler angles $(\alpha,\ \beta,\ \gamma)$
- $|\psi^J_{MK}(\alpha)\rangle$ projected from different intrinsic states are not in general orthogonal to each other

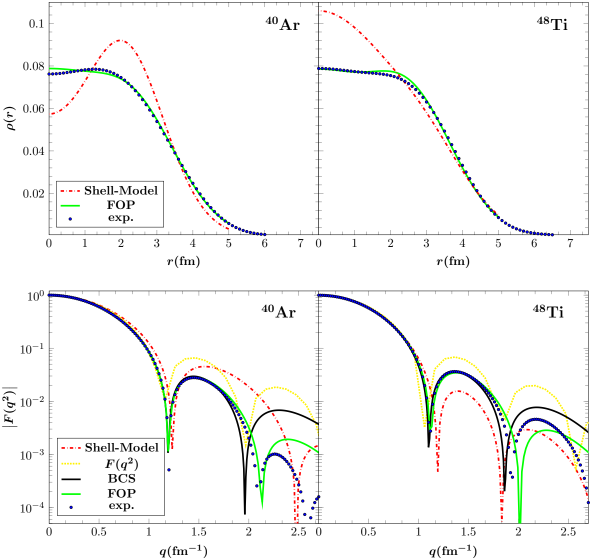
Band mixing calculations are performed after appropriate orthonormalization. The resulting eigenfunctions are of the form

$$|\Phi^J_M(\eta)\rangle = \sum_{K,\alpha} S^J_{K\eta}(\alpha) |\psi^J_{MK}(\alpha)\rangle , \qquad S^J_{K\eta}(\alpha) : \text{ expansion coefficients}$$

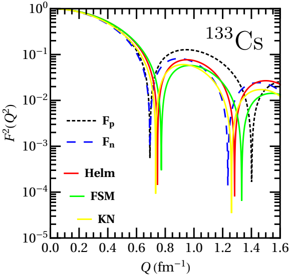
The nuclear matrix elements occurring in the calculation of magnetic moments, elastic and inelastic spin structure functions etc. are evaluated using the wave functions $|\Phi^J_M(\eta)\rangle$.

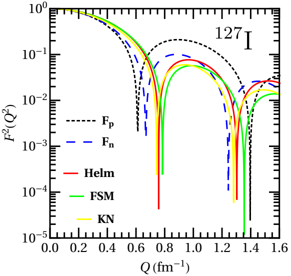
Comparison of the nuclear methods

DKP, Kosmas, Adv.High Energy Phys. **2015** (2015) 763648

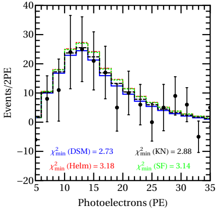


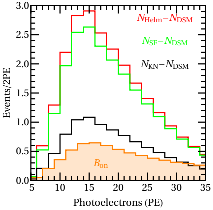
Impact of form factor on CEνNS: COHERENT exp.

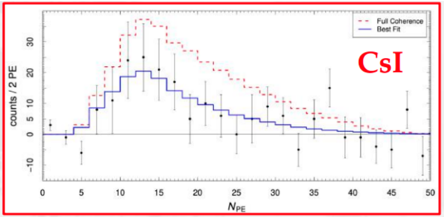




[DKP, Kosmas, Sahu, Kota, Hota PLB 800 (2020) 135133]

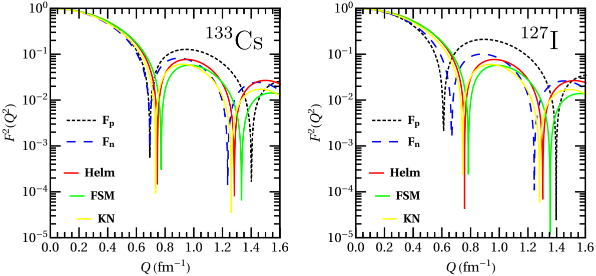




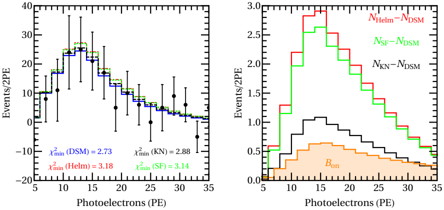


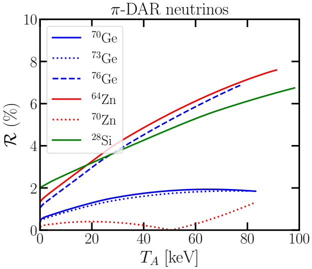
M. Cadeddu et al. - Phys.Rev.D 101 (2020) 3, 033004

Impact of form factor on CEνNS: COHERENT exp.



[DKP, Kosmas, Sahu, Kota, Hota PLB 800 (2020) 135133]





Up to 8% difference in the theoretical event rates

Incoherent neutrino-nucleus scattering

Naumov Bednyakov formalism

$$\frac{d\sigma_{\text{inc}}}{dT_A} = \frac{4G_F^2 m_A}{\pi} \sum_{f=n,p} g_{\text{inc}}^f \left(1 - |F_f|^2\right) \times \left[A_+^f \left(\left(g_{L,f} - g_{R,f}ab^2\right)^2 + g_{R,f}^2 ab^2(1-a)\right) + A_-^f g_{R,f}^2 (1-a)\left(1 - a + ab^2\right)\right]. \quad (1)$$

$$a = \frac{q^2}{q_{\text{min}}^2} \simeq \frac{T_A}{T_A^{\text{max}}}, \quad b^2 = \frac{m_f^2}{s}. \quad (2)$$

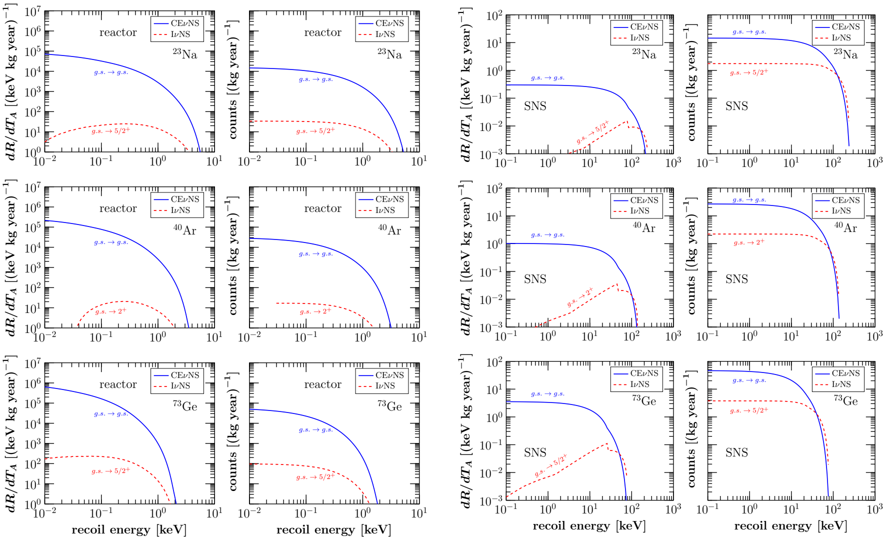
Here, $A_\pm^p \equiv Z_\pm$ ($A_\pm^n \equiv N_\pm$) represents the number of protons (neutrons) with spin $\pm 1/2$ and $s = (p+k)^2$ is the total energy squared in the center-of-mass frame (p denotes an effective 4-momentum of the nucleon).

[Bednyakov, Naumov, PRD 98 (2018) 053004]

For a more detailed study see: [Hoferichter, Menéndez, Schwenk PRD 102, 074018]

Incoherent vs. Coherent rates: πDAR and reactors

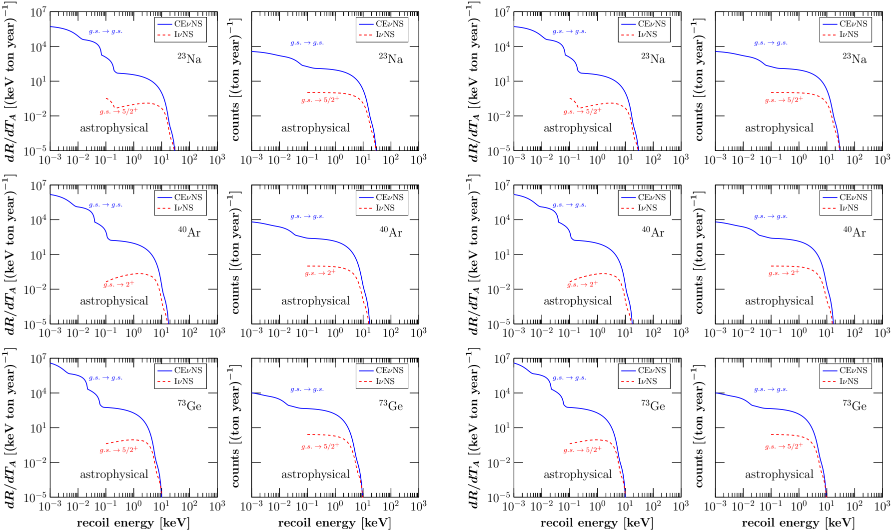
reactor neutrinos | **πDAR neutrinos**



[Sahu, DKP, Kota, Kosmas, PRC 102 (2020) 3, 035501]

Incoherent vs. Coherent rates: solar neutrinos

Solar neutrinos



[Sahu, DKP, Kota, Kosmas, PRC 102 (2020) 3, 035501]

Incoherent calculations: multipole expansion

- Interaction Hamiltonian for neutral-current (NC) neutrino-nucleus scattering

$$\langle f|\hat{H}_{eff}|i\rangle = \frac{G_F}{\sqrt{2}} \int d^3\mathbf{x}\, \langle \ell_f|\hat{j}_\mu^{lept}(\mathbf{x})|\ell_i\rangle \langle J_f|\hat{\mathcal{J}}^\mu(\mathbf{x})|J_i\rangle$$

with $\langle \ell_f|\hat{j}_\mu^{lept}|\ell_i\rangle = \bar{\nu}_\alpha \gamma_\mu (1-\gamma_5)\nu_\alpha\, e^{-i\mathbf{q}\cdot\mathbf{x}}$, $\quad \mathbf{q}: 3-\text{momentum transfer}$

- In the Donnelly-Walecka multipole decomposition method, the NC, double diff. SM cross section from an initial $|J_i\rangle$ to a final $|J_f\rangle$ nuclear state (constructed explicitly through QRPA realistic nuclear structure calculations), reads

$$\boxed{\frac{d^2\sigma_{i\to f}}{d\Omega\, d\omega} = \frac{G_F^2}{\pi}\frac{\varepsilon_i \varepsilon_f}{(2J_i+1)}\left(\sum_{J=0}^{\infty} \sigma_{\mathrm{CL}}^J + \sum_{J=1}^{\infty}\sigma_{\mathrm{T}}^J\right)} \ ,$$

ε_i (ε_f) is the initial (final) neutrino energy and ω is the nucleus excitation energy.

- Contributions to σ_{CL}^J (Coulomb-longitudinal) and σ_{T}^J (transverse electric-magnetic) components [Donnelly and Peccei, Phys. Rept. **50** (1979) 1]

$$\begin{aligned}
\sigma_{\mathrm{CL}}^J =&(1+a\cos\theta)|\langle J_f||\hat{\mathcal{M}}_J(\kappa)||J_i\rangle|^2 + (1+a\cos\theta - 2b\sin^2\theta)|\langle J_f||\hat{\mathcal{L}}_J(\kappa)||J_i\rangle|^2 \\
&+ \left[\frac{\omega}{\kappa}(1+a\cos\theta)+d\right] 2\Re e|\langle J_f||\hat{\mathcal{L}}_J(\kappa)||J_i\rangle||\langle J_f||\hat{\mathcal{M}}_J(\kappa)||J_i\rangle|^* \,, \\
\sigma_{\mathrm{T}}^J =&(1-a\cos\theta+b\sin^2\theta)\left[|\langle J_f||\hat{\mathcal{T}}_J^{mag}(\kappa)||J_i\rangle|^2 + |\langle J_f||\hat{\mathcal{T}}_J^{el}(\kappa)||J_i\rangle|^2\right] \\
&\mp \left[\frac{(\varepsilon_i+\varepsilon_f)}{\kappa}(1-a\cos\theta)-d\right] 2\Re e|\langle J_f||\hat{\mathcal{T}}_J^{mag}(\kappa)||J_i\rangle||\langle J_f||\hat{\mathcal{T}}_J^{el}(\kappa)||J_i\rangle|^*
\end{aligned}$$

from kinematics: $a=1$, $b=\varepsilon_i\varepsilon_f/\kappa^2$, $d=0$ and $\kappa=|\mathbf{q}|$

Evaluation of the Nuclear Matrix Elements

- Seven new operators are defined (proton-neutron representation) as

$$
\begin{aligned}
T_1^{JM} &\equiv M_M^J(\kappa \mathbf{r}) \;=\; \delta_{LJ}\, j_L(\kappa \mathbf{r}) Y_M^L(\hat{r}),\\
T_2^{JM} &\equiv \Sigma_M^J(\kappa \mathbf{r}) \;=\; \mathbf{M}_M^{JJ} \cdot \boldsymbol{\sigma},\\
T_3^{JM} &\equiv \Sigma'^J_M(\kappa \mathbf{r}) \;=\; -i\left[\frac{1}{\kappa}\boldsymbol{\nabla} \times \mathbf{M}_M^{JJ}(\kappa \mathbf{r})\right] \cdot \boldsymbol{\sigma},\\
T_4^{JM} &\equiv \Sigma''^J_M(\kappa \mathbf{r}) \;=\; \left[\frac{1}{\kappa}\boldsymbol{\nabla} M_M^J(\kappa \mathbf{r})\right] \cdot \boldsymbol{\sigma},\\
T_5^{JM} &\equiv \Delta_M^J(\kappa \mathbf{r}) \;=\; \mathbf{M}_M^{JJ}(\kappa \mathbf{r}) \cdot \frac{1}{\kappa}\boldsymbol{\nabla},\\
T_6^{JM} &\equiv \Delta'^J_M(\kappa \mathbf{r}) \;=\; -i\left[\frac{1}{\kappa}\boldsymbol{\nabla} \times \mathbf{M}_M^{JJ}(\kappa \mathbf{r})\right] \cdot \frac{1}{\kappa}\boldsymbol{\nabla},\\
T_7^{JM} &\equiv \Omega_M^J(\kappa \mathbf{r}) \;=\; M_M^J(\kappa \mathbf{r})\boldsymbol{\sigma} \cdot \frac{1}{\kappa}\boldsymbol{\nabla}\,.
\end{aligned}
$$

Closed compact analytic formulae for the single-particle reduced ME (upper) and many-body reduced ME (lower) for QRPA calculations, are deduced.

$$
\langle (n_1\ell_1)j_1 || T_i^J || (n_2\ell_2)j_2 \rangle = e^{-y} y^{\beta/2} \sum_{\mu=0}^{n_{max}} \mathcal{P}_\mu^{i,\,J} y^\mu, \quad y = (\kappa b/2)^2, \quad n_{max} = (N_1 + N_2 - \beta)/2, \quad N_i = 2n_i + \ell_i
$$

$$
\langle f \| \widehat{T}^J \| 0_{gs}^+ \rangle = \sum_{j_2 \geq j_1} \frac{\langle j_2 \| \widehat{T}^J \| j_1 \rangle}{\hat{J}} \left[X_{j_2 j_1} u_{j_2}^{p(n)} v_{j_1}^{p(n)} + Y_{j_2 j_1} v_{j_2}^{p(n)} u_{j_1}^{p(n)} \right]
$$

[Chasioti, Kosmas NPA 829 (2009) 234]
P.G. Giannaka, D.K. Papoulias, T.S. Kosmas, unpublished (for any configuration $(j_1, j_2)J$)

Electromagnetic neutrino properties

Electromagnetic contribution to CEνNS cross section

The Electromagnetic CEνNS cross section reads [Vogel, Engel.: PRD 39 [1989] 3378]

$$\left(\frac{d\sigma}{dT_A}\right)_{\mathrm{EM}} = \frac{\pi a_{\mathrm{EM}}^2 \mu_\nu^2 Z^2}{m_e^2} \left(\frac{1 - T_A/E_\nu}{T_A}\right) F^2(Q^2)\,.$$

- can be dominant for sub-keV threshold experiments
- may lead to detectable distortions of the recoil spectrum

The helicity preserving SM cross section adds incoherently with the helicity-violating EM cross section

$$\left(\frac{d\sigma}{dT_A}\right)_{\mathrm{tot}} = \left(\frac{d\sigma}{dT_A}\right)_{\mathrm{SM}} + \left(\frac{d\sigma}{dT_A}\right)_{\mathrm{EM}}$$

μ_ν^2 is the effective neutrino magnetic moment in the mass basis relevant to a given neutrino beam (reactor, SNS, etc.)

- Experimental measurements usually constrain some process-dependent effective parameter combination
- needs to be expressed in terms of fundamental parameters (TMMs + CP phases + mixing-angles)
- Even in the case of laboratory neutrino experiments, where the initial neutrino flux is fixed to have a well determined given flavor, there is no sensitivity to the final neutrino state

Analysis of the COHERENT data: EM properties

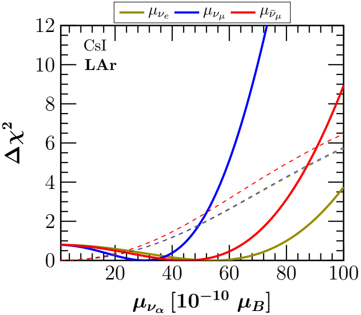
- **Neutrino magnetic moment contrbution**

$$\left(\frac{d\sigma}{dT_N}\right)_{\rm SM+EM} = \mathcal{G}_{\rm EM}(E_\nu, T_N)\frac{d\sigma_{\rm SM}}{dT_N},$$

$$\mathcal{G}_{\rm EM} = 1 + \frac{1}{G_F^2 M}\left(\frac{\mathcal{Q}_{\rm EM}}{\mathcal{Q}_W^V}\right)^2 \frac{\frac{1-T_N/E_\nu}{T_N}}{1-\frac{MT_N}{2E_\nu^2}}.$$

- **EM charge:** $\mathcal{Q}_{\rm EM} = \frac{\pi a_{\rm EM}\mu_{\nu_\alpha}}{m_e} Z$

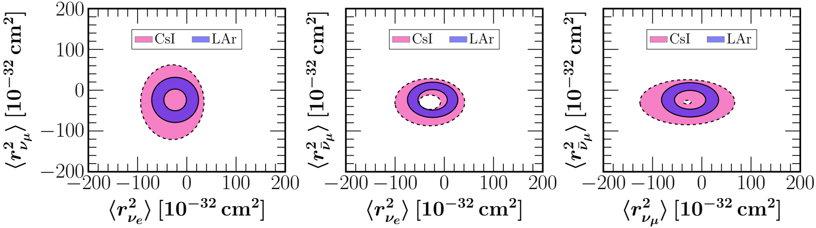
  [Vogel, Engel: PRD 39 [1989] 3378]



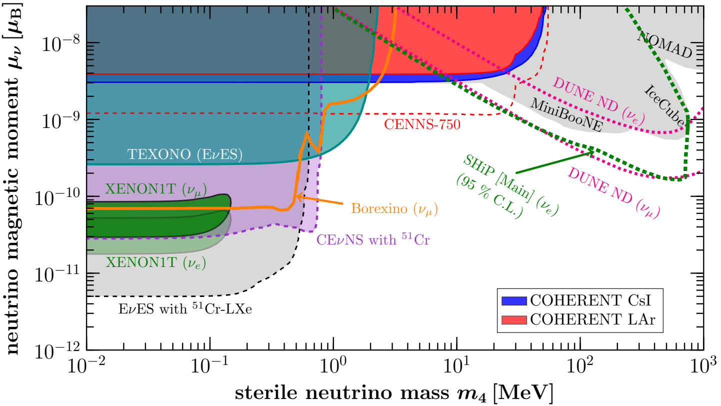
- **Neutrino charge radius**

$$\sin^2\theta_W \to \sin^2\overline{\theta_W} + \frac{\sqrt{2}\pi a_{\rm EM}}{3G_F}\langle r^2_{\nu_\alpha}\rangle.$$

Miranda et al. JHEP 05 (2020) 130



Active-sterile transitions via magnetic moment



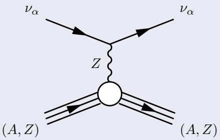
stay tuned! [Miranda, DKP, Sanders, Tórtola, arXiv:2109.XXXX]

poster ID#58 (room E) by Oscar Sanders

Summary

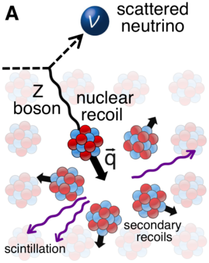
CEνNS

$$\nu_\alpha + (A, Z) \to \nu_\alpha + (A, Z), \quad \alpha = (e, \mu, \tau)$$



- Finally observed on CsI (2017) and LAr (2020)
  (other: MINER, TEXONO, CONNIE, Ricochet, νGEN, ν-cleus etc.)
- CONUS, CONNIE (hints)
- Very high experimental sensitivity (low detector threshold) is required

- largest theoretical uncertainty coming nuclear physics
- sensitive to nuclear charge radii
- can probe electromagnetic neutrino properties



Thank you for your attention !