Probing neutrino transition magnetic moments with coherent elastic neutrino-nucleus scattering

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talk based on arXiv:1905.03750, in collaboration with O. Miranda, M. Tórtola, J. Valle

Outline

1. Introduction
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     $\nu + (A, Z) \rightarrow \nu + (A, Z)$
   - Physics Motivations of neutrino-nucleus studies
   - CEνNS experiments
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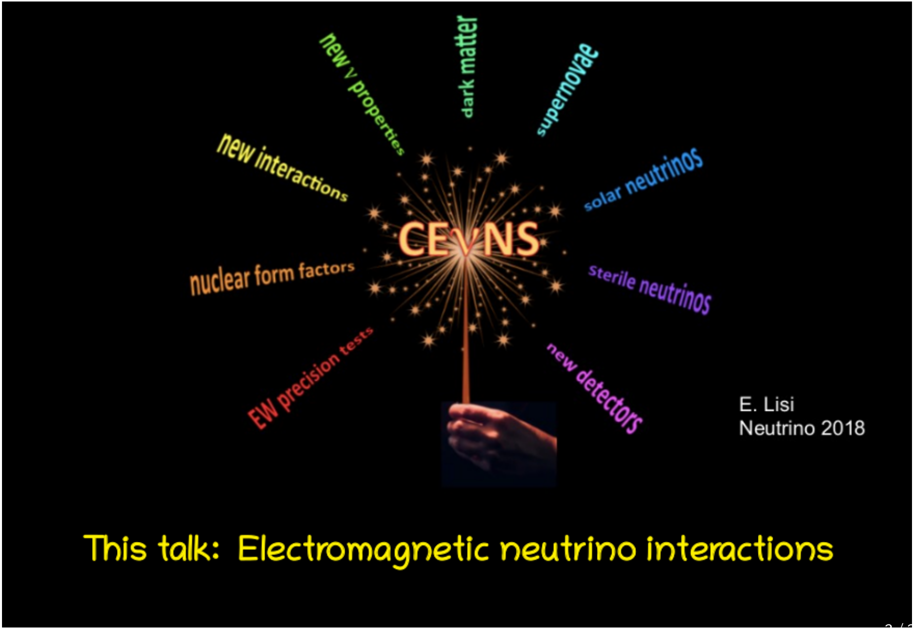
   - neutrino transition magnetic moments (TMMs)
   - EM contribution to SM CEνNS cross section
3. Results
   - CEνNS sensitivity on TMMs and future prospects
   - impact of CP violating phases
   - comparison with Borexino
4. Summary and Outlook

Physics Motivations of CEνNS



Science REPORTS

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Observation of coherent elastic neutrino-nucleus scattering

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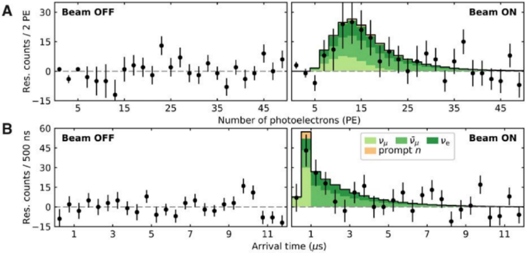
134 ± 22 events were measured at a 6.7-σ confidence level, using a low-background, 14.6-kg CsI[Na] scintillator within 308.1 live days

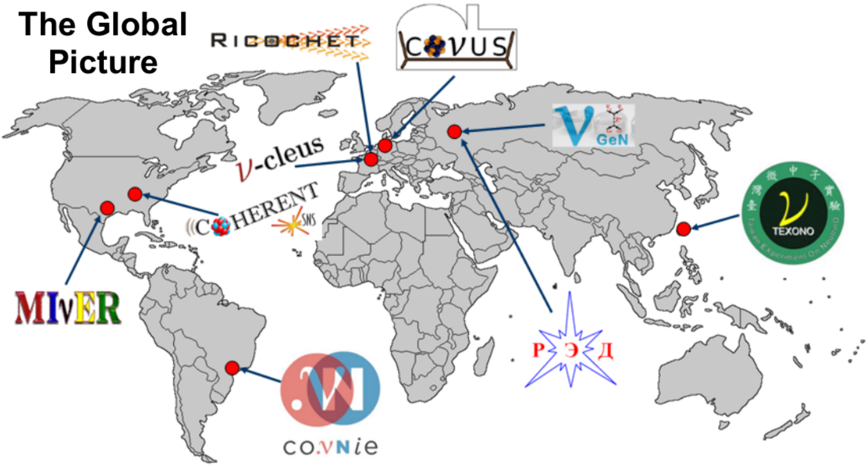


Members of the COHERENT team work with the world's smallest neutrino detector, the only one that can be lifted without heavy machinery. COHERENT COLLABORATION; PHOTOGRAPHER JUAN COLLAR

Milk jug–sized detector captures neutrinos in a whole new way

[COHERENT Collab. (Akimov et al.), Science **357** (2017) 1123]

CEνNS experiments worldwide



from M. Green: Aspen 2019 Winter Conference, March 2019

CEνNS is a very active field

...as of December 2018

- NSI
  - 1804.03660, 1711.09773 , 1711.03521, 1708.04255 , 1708.02899, 1612.04150, 1805.01798, 1812.02778
- SPVAT (S: 1, P: γ^5, V: γ^μ, A: $\gamma^\mu\gamma^5$, T: $\sigma^{\mu\nu}$)
  - 1806.07424, 1711.09773, 1612.04150, 1812.02778
- Sterile neutrinos
  - 1703.00054, 1711.09773, 1511.02834
- Light mediators (scalar, Z', dark photon...)
  - 1803.05466, 1803.01224, 1803.00060, 1802.05171, 1711.09773, 1711.04531, 1710.10889, 1612.06350, 1805.01798, 1508.07981, 1810.03626
- Neutrino electromagnetic properties
  - 1510.01684, 1706.02555, 1711.09773, 1805.01798, 1810.05606
- Dark matter
  - 1810.03626

from Xun-Jie Xu, presented at the *Quest for New Physics*, Valencia 2018

Analysis of the COHERENT data: SM

- **SM diff. cross section**

$$\frac{d\sigma_{\rm SM}}{dT_N}(E_\nu, T_N) = \frac{G_F^2 M}{\pi}\left[(\mathcal{Q}_W^V)^2\left(1-\frac{MT_N}{2E_\nu^2}\right) + (\mathcal{Q}_W^A)^2\left(1+\frac{MT_N}{2E_\nu^2}\right)\right]F^2(T_N)\,,$$

- **SM vector and axial vector couplings**

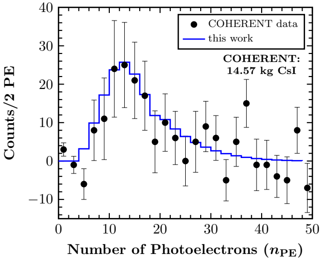
$$\mathcal{Q}_W^V = \left[g_p^V Z + g_n^V N\right]\,,$$
$$\mathcal{Q}_W^A = \left[g_p^A (Z_+ - Z_-) + g_n^A (N_+ - N_-)\right]\,,$$

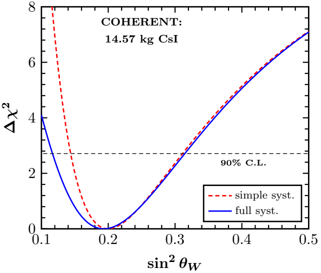
- **single-bin counting problem (flux, quenching factor, and acceptance uncertainties are incorporated)**

$$\chi^2(s_W^2) = \min_{\xi,\zeta}\left[\frac{\left(N_{\rm meas} - N_{\nu_\alpha}^{\rm SM}(s_W^2)[1+\xi] - B_{0n}[1+\zeta]\right)^2}{\sigma_{\rm stat}^2} + \left(\frac{\xi}{\sigma_\xi}\right)^2 + \left(\frac{\zeta}{\sigma_\zeta}\right)^2\right],$$

D.K. Papoulias and T.S. Kosmas, Phys.Rev. **D97** (2018) 033003

- **search between $6 \leq n_{\rm PE} \leq 30$**





for future perspectives see Cañas et al., Phys.Lett. B784 (2018) 159-162

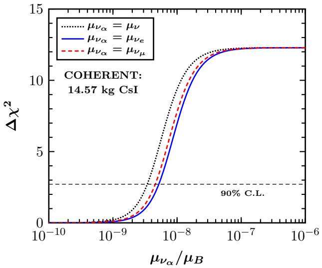
Analysis of the COHERENT data: EM properties

- **Neutrino magnetic moment contrbution**

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

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

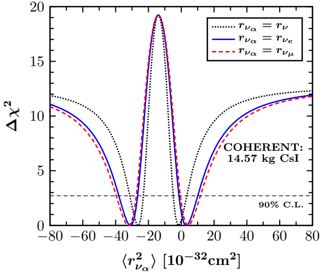
- **EM charge:** $\mathcal{Q}_{\mathrm{EM}} = \frac{\pi a_{\mathrm{EM}}\mu_{\nu_\alpha}}{m_e} Z$
  Vogel et al. Phys.Rev. D39 (1989) 3378



- **Neutrino charge radius**
- **redefinition of the weak mixing angle**

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

see also Cadeddu et al., arXiv:1810.05606



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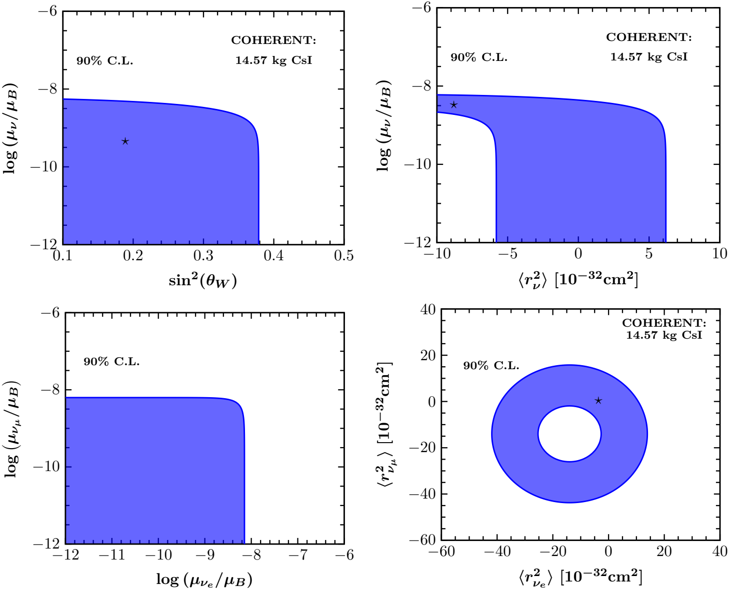
Analysis of the COHERENT data: combined constraints



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Electromagnetic neutrino vertex (spin component)

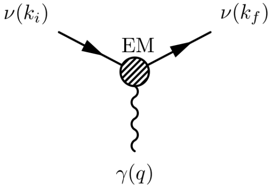
Dirac neutrinos: $H^{\mathrm{D}}_{\mathsf{EM}} = \frac{1}{2}\bar{\nu}_R \lambda \sigma^{\alpha\beta} \nu_L F_{\alpha\beta} + \mathrm{h.c.}$

- $\lambda = \mu - i\epsilon$ is a complex matrix
- $\mu = \mu^\dagger$ and $\epsilon = \epsilon^\dagger$.

Majorana neutrinos: $H^{\mathrm{M}}_{\mathsf{EM}} = -\frac{1}{4}\nu_L^{\mathsf{T}} C^{-1} \lambda \sigma^{\alpha\beta} \nu_L F_{\alpha\beta} + \mathrm{h.c.}$

- $\lambda = \mu - i\epsilon$: antisymmetric complex matrix $(\lambda_{\alpha\beta} = -\lambda_{\beta\alpha})$
- $\mu^{\mathsf{T}} = -\mu$ and $\epsilon^{\mathsf{T}} = -\epsilon$ are two imaginary matrices.
- three complex or six real parameters are required

In contrast to the Dirac case, vanishing diagonal moments are implied for Majorana neutrinos, $\mu^{\mathrm{M}}_{ii} = \epsilon^{\mathrm{M}}_{ii} = 0$.



[Schechter, Valle: PRD 24 (1981), PRD 25 (1982)]

The neutrino transition magnetic moment (TMM) matrix

The magnetic moment matrix λ ($\tilde{\lambda}$) in the flavor (mass) basis reads

[Tórtola: PoS AHEP 2003 (2003)]

$$\lambda = \begin{pmatrix} 0 & \Lambda_\tau & -\Lambda_\mu \\ -\Lambda_\tau & 0 & \Lambda_e \\ \Lambda_\mu & -\Lambda_e & 0 \end{pmatrix}, \qquad \tilde{\lambda} = \begin{pmatrix} 0 & \Lambda_3 & -\Lambda_2 \\ -\Lambda_3 & 0 & \Lambda_1 \\ \Lambda_2 & -\Lambda_1 & 0 \end{pmatrix}$$

- the definition $\lambda_{\alpha\beta} = \varepsilon_{\alpha\beta\gamma}\Lambda_\gamma$ has been introduced,
- the neutrino TMMs are represented by the complex parameters

$$\Lambda_\alpha = |\Lambda_\alpha| e^{i\zeta_\alpha}, \qquad \Lambda_i = |\Lambda_i| e^{i\zeta_i}$$

three complex or six real parameters (3 moduli + 3 phases)

Effective neutrino magnetic moment @ experiments

Is expressed in terms of the neutrino magnetic moment matrix and the amplitudes of positive and negative helicity states 3−vectors $\mathfrak{a}_+$ and $\mathfrak{a}_-$,

- In the flavor basis one finds [Grimus, Schwetz: Nucl. Phys. B587 (2000)]

$$\left(\mu_\nu^F\right)^2 = \mathfrak{a}_-^\dagger \lambda^\dagger \lambda \mathfrak{a}_- + \mathfrak{a}_+^\dagger \lambda \lambda^\dagger \mathfrak{a}_+ \,,$$

Introducing the transformations (U is the lepton mixing matrix)

$$\tilde{\mathfrak{a}}_- = U^\dagger \mathfrak{a}_-, \qquad \tilde{\mathfrak{a}}_+ = U^\mathsf{T} \mathfrak{a}_+, \qquad \tilde{\lambda} = U^\mathsf{T} \lambda U \,,$$

- In the mass basis reads

$$\left(\mu_\nu^M\right)^2 = \tilde{\mathfrak{a}}_-^\dagger \tilde{\lambda}^\dagger \tilde{\lambda} \tilde{\mathfrak{a}}_- + \tilde{\mathfrak{a}}_+^\dagger \tilde{\lambda} \tilde{\lambda}^\dagger \tilde{\mathfrak{a}}_+$$

TMMs in flavor & mass basis @ reactor facilities

Reactor antineutrinos: $\bar{\nu}_e$ (where $\mathfrak{a}_+^1 = 1$)

- flavor basis

$$\left(\mu^F_{\bar{\nu}_e,\,\text{reactor}}\right)^2 = |\Lambda_\mu|^2 + |\Lambda_\tau|^2$$

where $|\Lambda_\mu|$ and $|\Lambda_\tau|$ are the elements of the neutrino TMM matrix λ describing the corresponding conversions from the electron antineutrino to the muon and tau neutrino states

- mass basis [Cañas et al.: PLB 753 (2016)]

$$\begin{aligned}\left(\mu^M_{\bar{\nu}_e,\,\text{reactor}}\right)^2 =& |\mathbf{\Lambda}|^2 - c_{12}^2 c_{13}^2 |\Lambda_1|^2 - s_{12}^2 c_{13}^2 |\Lambda_2|^2 - s_{13}^2 |\Lambda_3|^2 \\ &- c_{13}^2 \sin 2\theta_{12} |\Lambda_1||\Lambda_2| \cos\xi_3 \\ &- c_{12} \sin 2\theta_{13} |\Lambda_1||\Lambda_3| \cos(\delta_{CP} - \xi_2) \\ &- s_{12} \sin 2\theta_{13} |\Lambda_2||\Lambda_3| \cos(\delta_{CP} - \xi_1)\,,\end{aligned}$$

with $|\mathbf{\Lambda}|^2 = |\Lambda_1|^2 + |\Lambda_2|^2 + |\Lambda_3|^2$ and

phase redefinition: $\xi_1 = \zeta_3 - \zeta_2$, $\xi_2 = \zeta_3 - \zeta_1$ and $\xi_3 = \zeta_1 - \zeta_2$

TMMs in flavor & mass basis @ SNS facilities (prompt)

Prompt beam: ν_μ (with $\mathfrak{a}_-^2 = 1$)

- flavor basis

$$\left(\mu^F_{\nu_\mu,\,\text{prompt}}\right)^2 = |\Lambda_e|^2 + |\Lambda_\tau|^2$$

- mass basis

$$\begin{aligned}
\left(\mu^M_{\nu_\mu,\,\text{prompt}}\right)^2 = & |\Lambda_1|^2 \left[-2 c_{12} c_{23} s_{12} s_{13} s_{23} \cos\delta_{CP} \right. \\
& \left. \qquad + s_{23}^2\left(c_{13}^2 + s_{12}^2 s_{13}^2\right) + c_{12}^2 c_{23}^2\right] \\
& + |\Lambda_2|^2 \left[2 c_{12} c_{23} s_{13} s_{23} s_{12} \cos\delta_{CP} + c_{23}^2 s_{12}^2 + s_{23}^2\left(c_{12}^2 s_{13}^2 + c_{13}^2\right)\right] \\
& + |\Lambda_3|^2 \left[c_{23}^2 + s_{13}^2 s_{23}^2\right] \\
& + 2\,|\Lambda_1 \Lambda_2| \left[c_{23} c_{12}^2 s_{13} s_{23} \cos\left(\delta_{CP} + \xi_3\right) - c_{23} s_{12}^2 s_{13} s_{23} \cos\left(\delta_{CP} - \xi_3\right) \right. \\
& \left. \qquad + c_{12} s_{12}\left(c_{23}^2 - s_{13}^2 s_{23}^2\right) \cos\xi_3\right] \\
& + 2\,|\Lambda_1 \Lambda_3| \left[c_{13} s_{23}\left(c_{12} s_{13} s_{23} \cos\left(\delta_{CP} - \xi_2\right) + c_{23} s_{12} \cos\xi_2\right)\right] \\
& + 2\,|\Lambda_2 \Lambda_3| \left[c_{13} s_{23}\left(s_{12} s_{13} s_{23} \cos\left(\delta_{CP} - \xi_1\right) - c_{12} c_{23} \cos\xi_1\right)\right] .
\end{aligned}$$

Miranda, DKP, Tórtola, Valle, arXiv:1905.03750

TMMs in flavor & mass basis @ SNS facilities (delayed ν_e)

Delayed beam: (i) ν_e (with $\mathfrak{a}_-^1 = 1$) and (ii) $\bar{\nu}_\mu$ (with $\mathfrak{a}_+^2 = 1$)

Focus on the ν_e component

- flavor basis

$$\left(\mu^F_{\nu_e,\,\text{delayed}}\right)^2 = |\Lambda_\mu|^2 + |\Lambda_\tau|^2$$

- mass basis

$$\begin{aligned}\left(\mu^M_{\nu_e,\,\text{delayed}}\right)^2 &= |\Lambda_1|^2\left[c_{13}^2 s_{12}^2 + s_{13}^2\right] + |\Lambda_2|^2\left[c_{12}^2 c_{13}^2 + s_{13}^2\right] + |\Lambda_3|^2\, c_{13}^2 \\ &- |\Lambda_1\Lambda_2|\left[c_{13}^2 \sin(2\theta_{12})\cos\xi_3\right] - |\Lambda_1\Lambda_3|\left[c_{12}\sin(2\theta_{13})\cos(\delta_{\text{CP}} - \xi_2)\right] \\ &- |\Lambda_2\Lambda_3|\left[s_{12}\sin(2\theta_{13})\cos(\delta_{\text{CP}} - \xi_1)\right] \,,\end{aligned}$$

Miranda, DKP, Tórtola, Valle, arXiv:1905.03750

TMMs in flavor & mass basis @ SNS facilities (delayed $\bar{\nu}_\mu$)

Delayed beam: (i) ν_e (with $\mathfrak{a}^1_- = 1$) and (ii) $\bar{\nu}_\mu$ (with $\mathfrak{a}^2_+ = 1$)

Focus on the $\bar{\nu}_\mu$ component

- flavor basis

$$\left(\mu^F_{\bar{\nu}_\mu,\,\text{delayed}}\right)^2 = |\Lambda_e|^2 + |\Lambda_\tau|^2$$

- mass basis

$$\begin{aligned}
\left(\mu^M_{\bar{\nu}_\mu,\,\text{delayed}}\right)^2 = & |\Lambda_1|^2 \left[-2c_{12}c_{23}s_{12}s_{13}s_{23}\cos\delta_{\text{CP}} + s_{23}^2\left(c_{13}^2 + s_{12}^2 s_{13}^2\right) + c_{12}^2 c_{23}^2\right] \\
& + |\Lambda_2|^2 \left[2c_{12}c_{23}s_{12}s_{13}s_{23}\cos\delta_{\text{CP}} + s_{23}^2\left(c_{13}^2 + c_{12}^2 s_{13}^2\right) + s_{12}^2 c_{23}^2\right] \\
& + |\Lambda_3|^2 \left[\frac{1}{4}\left(2c_{13}^2\cos(2\theta_{23}) - \cos(2\theta_{13}) + 3\right)\right] \\
& + 2\,|\Lambda_1\Lambda_2| \left[c_{23}s_{13}s_{23}\left(c_{12}^2\cos\left(\delta_{\text{CP}} + \xi_3\right) - s_{12}^2\cos\left(\delta_{\text{CP}} - \xi_3\right)\right)\right. \\
& \left. + c_{12}c_{23}^2 s_{12}\cos\xi_3 - c_{12}s_{12}s_{13}^2 s_{23}^2\cos\xi_3\right] \\
& + 2\,|\Lambda_1\Lambda_3| \left[c_{13}s_{23}\left(c_{12}s_{13}s_{23}\cos\left(\delta_{\text{CP}} - \xi_2\right) + c_{23}s_{12}\cos\xi_2\right)\right] \\
& + 2\,|\Lambda_2\Lambda_3| \left[c_{13}s_{23}\left(s_{12}s_{13}s_{23}\cos\left(\delta_{\text{CP}} - \xi_1\right) - c_{12}c_{23}\cos\xi_1\right)\right]
\end{aligned}$$

Miranda, DKP, Tórtola, Valle, arXiv:1905.03750

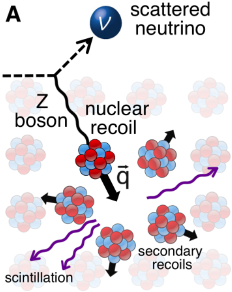
Standard Model CEνNS cross section

CEνNS cross section expressed through the nuclear recoil energy T_A

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

[Papoulias, 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)]

Evaluation of the form factors (Symmetrized Fermi)

Adopting a conventional Fermi (Woods-Saxon) charge density distribution, the SF form factor is written in terms of two parameters (c, a)

$$F_{\rm SF}\left(Q^2\right) = \frac{3}{Qc\left[(Qc)^2 + (\pi Qa)^2\right]}\left[\frac{\pi Qa}{\sinh(\pi Qa)}\right]\left[\frac{\pi Qa \sin(Qc)}{\tanh(\pi Qa)} - Qc\cos(Qc)\right],$$

The first three moments

$$\begin{aligned}
\left\langle R_n^2 \right\rangle &= \frac{3}{5}c^2 + \frac{7}{5}(\pi a)^2 \\
\left\langle R_n^4 \right\rangle &= \frac{3}{7}c^4 + \frac{18}{7}(\pi a)^2 c^2 + \frac{31}{7}(\pi a)^4 \\
\left\langle R_n^6 \right\rangle &= \frac{1}{3}c^6 + \frac{11}{3}(\pi a)^2 c^4 + \frac{239}{15}(\pi a)^4 c^2 + \frac{127}{5}(\pi a)^6 .
\end{aligned}$$

- c: half-density radius
- a fm: diffuseness
- surface thickness: $t = 4a \ln 3$

J.D. Lewin and P.F. Smith, Astropart.Phys. 6 (1996) 87-112

Electromagnetic contribution to CEνNS cross section

The Electromagnetic CEνNS cross section reads [Kosmas et al.: PRD 92 (2015)]

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

- 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 [Kosmas et al.: PLB 750 (2015)]

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

$\boldsymbol{\mu_\nu}$ is the effective neutrino magnetic moment in the mass basis relevant to a given neutrino beam (reactor, SNS, etc.)

Experimental configuration

Miranda, DKP, Tórtola, Valle, arXiv:1905.03750

Experiment	detector	mass	threshold	efficiency	exposure	baseline (m)
			SNS			
COHERENT	CsI[Na]	14.57 kg [100 kg]	5 keV [1 keV]	Eq. (**??**) [100%]	308.1 days [10 yr]	19.3
COHERENT	HPGe	15 kg [100 kg]	5 keV [1 keV]	50% [100%]	308.1 days [10 yr]	22
COHERENT	LAr	1 ton [10 ton]	20 keV [10 keV]	50% [100%]	308.1 days [10 yr]	29
COHERENT	NaI[Tl]	2 ton [10 ton]	13 keV [5 keV]	50% [100%]	308.1 days [10 yr]	28
			Reactor			
CONUS	Ge	3.85 kg [100 kg]	100 eV	50% [100%]	1 yr [10 yr]	17
CONNIE	Si	1 kg [100 kg]	28 eV	50% [100%]	1 yr [10 yr]	30
MINER	2Ge:1Si	1 kg [100 kg]	100 eV	50% [100%]	1 yr [10 yr]	2
TEXONO	Ge	1 kg [100 kg]	100 eV	50% [100%]	1 yr [10 yr]	28
RED100	Xe	100 kg [100 kg]	500 eV	50% [100%]	1 yr [10 yr]	19

Calculation of the number of events above threshold

$$N_{\rm theor} = \sum_{\nu_\alpha} \sum_{x=\rm isotope} \mathcal{F}_x \int_{T_{\rm th}}^{T_A^{\rm max}} \int_{E_\nu^{\rm min}}^{E_\nu^{\rm max}} f_{\nu_\alpha}(E_\nu)\mathcal{A}(T_A) \left(\frac{d\sigma_x}{dT_A}(E_\nu, T_A)\right)_{\rm tot} dE_\nu dT_A \,,$$

- luminosity for a detector with target material x: $\mathcal{F}_x = N_{\rm targ}^x \Phi_\nu$
- $E_\nu^{\rm min} = \sqrt{m_A T_A/2}$: the minimum incident neutrino energy to produce a nuclear recoil

Statistical analysis

First phase of COHERENT (with a CsI detector)

$$\chi^2(\mathcal{S}) = \min_{\mathrm{a}_1,\mathrm{a}_2}\left[\frac{(N_{\mathrm{meas}} - N_{\mathrm{theor}}(\mathcal{S})[1+\mathrm{a}_1] - B_{0n}[1+\mathrm{a}_2])^2}{(\sigma_{\mathrm{stat}})^2} + \left(\frac{\mathrm{a}_1}{\sigma_{\mathrm{a}_1}}\right)^2 + \left(\frac{\mathrm{a}_2}{\sigma_{\mathrm{a}_2}}\right)^2\right].$$

- measured number of events is $N_{\mathrm{meas}} = 142$,
- a_1 and a_2 are the systematic uncertainties (signal and background rates), with $\sigma_{\mathrm{a}_1} = 0.28$ and $\sigma_{\mathrm{a}_2} = 0.25$.
- Statistical uncertainty $\sigma_{\mathrm{stat}} = \sqrt{N_{\mathrm{meas}} + B_{0n} + 2B_{ss}}$, where the quantities $B_{0n} = 6$ and $B_{ss} = 405$ denote the beam-on prompt neutron and the steady-state background events respectively.

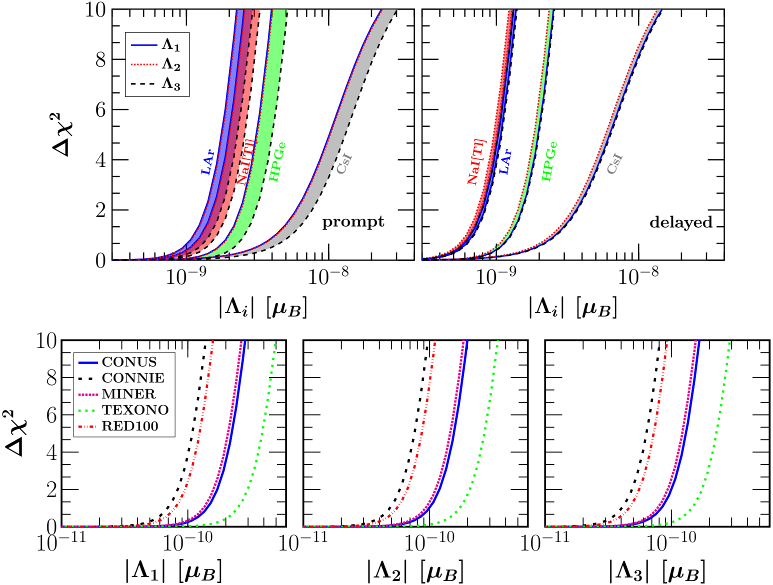
Reactor experiments and next generation of COHERENT

$$\chi^2(\mathcal{S}) = \min_{\mathrm{a}}\left[\frac{(N_{\mathrm{meas}} - N_{\mathrm{theor}}(\mathcal{S})[1+\mathrm{a}])^2}{(1+\sigma_{\mathrm{stat}})N_{\mathrm{meas}}} + \left(\frac{\mathrm{a}}{\sigma_{\mathrm{sys}}}\right)^2\right],$$

- with $\sigma_{stat} = \sigma_{\mathrm{sys}} = 0.2$ (0.1) for the current (future) setups.

Probe TMMs through minimization over the nuisance parameter a and calculate $\Delta\chi^2(\mathcal{S}) = \chi^2(\mathcal{S}) - \chi^2_{\mathrm{min}}(\mathcal{S})$, with $\mathcal{S} \equiv \{|\Lambda_i|, \xi_i, \delta_{\mathrm{CP}}\}$

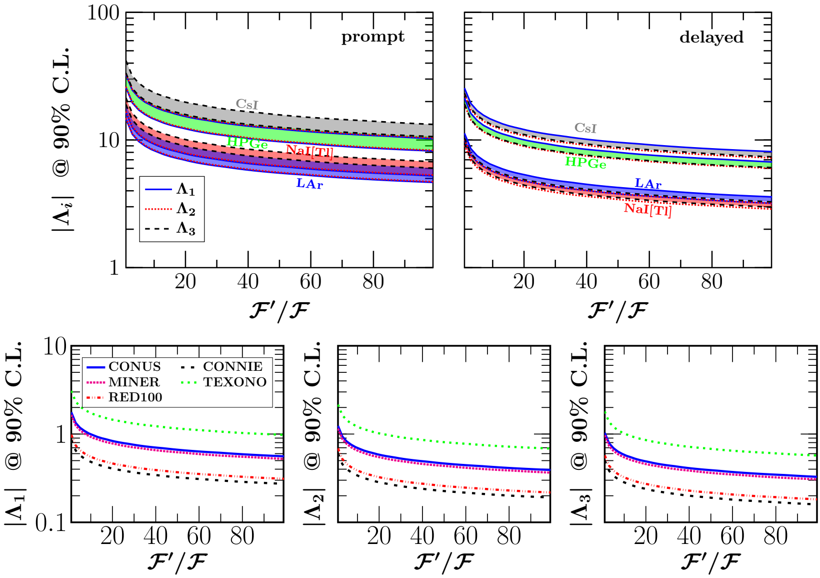
Analysis of CEνNS data: sensitivity to $|\Lambda_i|$



all results in units $10^{-10}\mu_B$

Miranda, DKP, Tórtola, Valle, arXiv:1905.03750

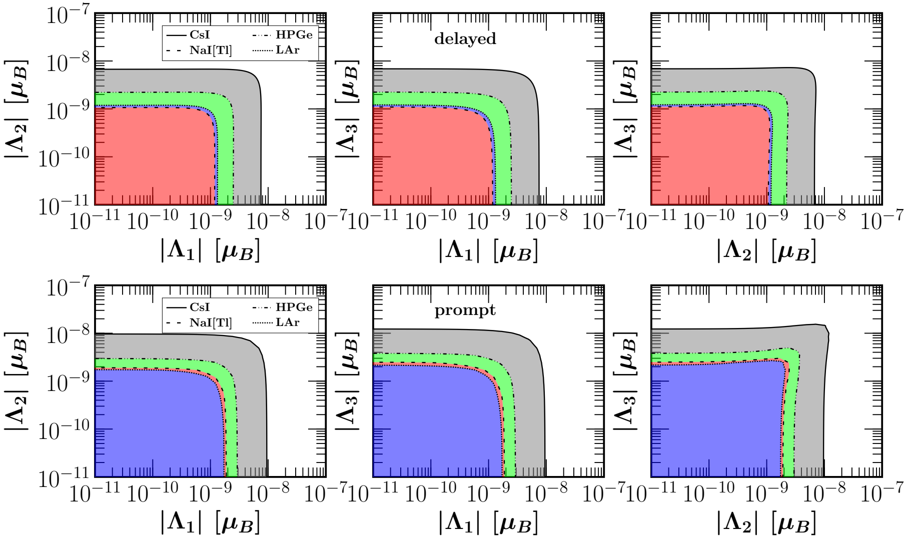
Analysis of CEνNS data: luminosity factor variation



all results in units $10^{-10}\mu_B$

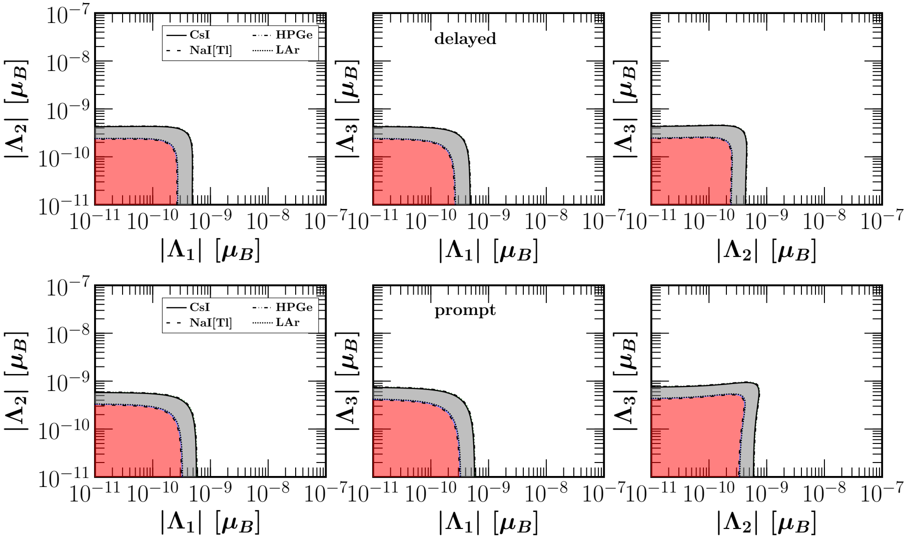
Miranda, DKP, Tórtola, Valle, arXiv:1905.03750

Current COHERENT setup: combined constraints



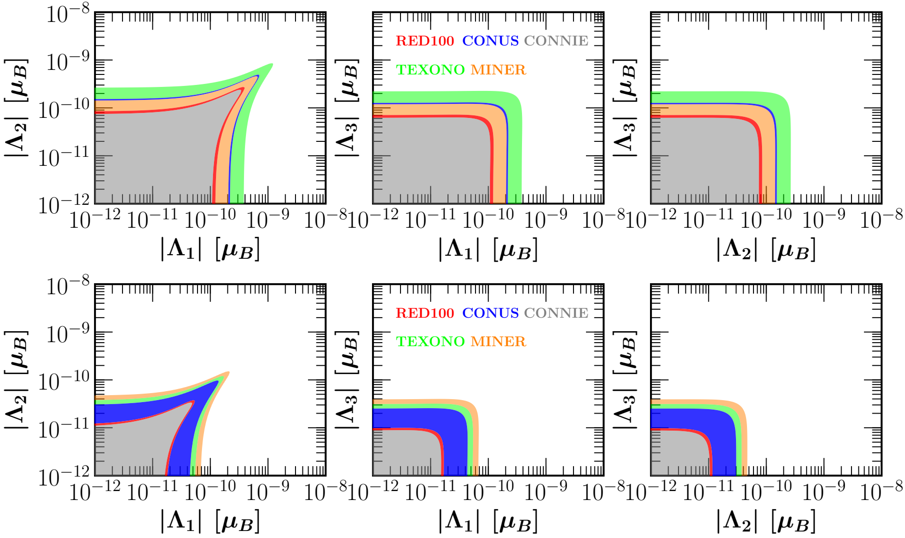
Miranda, DKP, Tórtola, Valle, arXiv:1905.03750

Future COHERENT setup: combined constraints



Miranda, DKP, Tórtola, Valle, arXiv:1905.03750

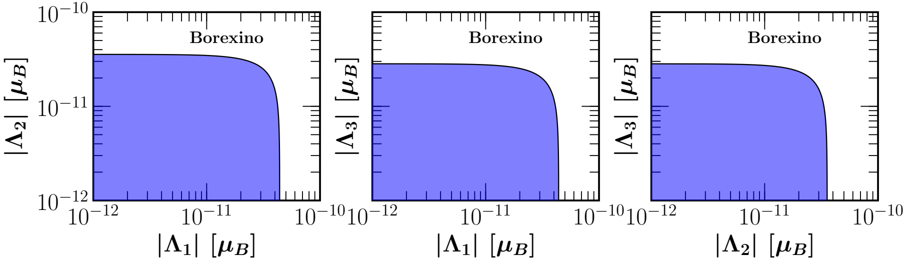
Current & Future Reactor experiments: combined constraints



Miranda, DKP, Tórtola, Valle, arXiv:1905.03750

Solar neutrinos from Borexino

Miranda, DKP, Tórtola, Valle, arXiv:1905.03750



- dependence on neutrino mixing and oscillation factor between the source and detection is considered
- the oscillation probabilities from ν_e to mass eigenstates ν_i are approximated

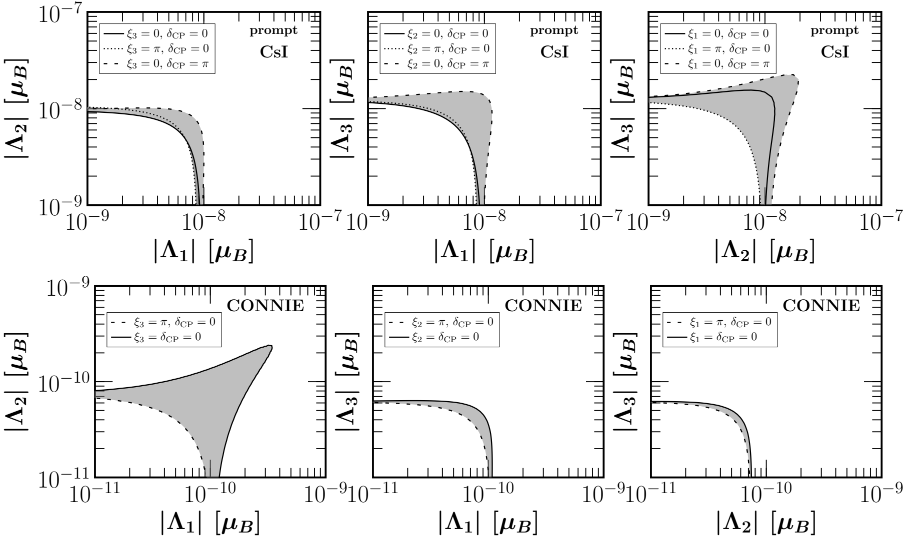
$$P_{e3}^{3\nu} = \sin^2\theta_{13}, \quad P_{e1}^{3\nu} = \cos^2\theta_{13} P_{e1}^{2\nu}, \quad P_{e2}^{3\nu} = \cos^2\theta_{13} P_{e2}^{2\nu},$$

  and the unitarity condition, $P_{e1}^{2\nu} + P_{e2}^{2\nu} = 1$
- effective neutrino magnetic moment for solar neutrinos in mass basis
  [Cañas et al.: PLB 753 (2016)]

$$(\mu_{\nu,\,\mathrm{sol}}^{M})^2 = |\boldsymbol{\Lambda}|^2 - c_{13}^2|\Lambda_2|^2 + (c_{13}^2 - 1)|\Lambda_3|^2 + c_{13}^2 P_{e1}^{2\nu}(|\Lambda_2|^2 - |\Lambda_1|^2)$$

- Recall Borexino phase-II limit $\mu_\nu < 2.8 \times 10^{-11}\mu_B$ [Borexino Collab., Agostini et al.:PRD 96 (2017)]
- no phase dependence, since solar electron neutrinos undergo flavor oscillations arriving to the detector as an incoherent admixture of mass eigenstates

Impact of CP phases



explore the robustness of TMMs limits

Miranda, DKP, Tórtola, Valle, arXiv:1905.03750

Summary

Experiment	$\lvert\Lambda_1\rvert$	$\lvert\Lambda_2\rvert$	$\lvert\Lambda_3\rvert$
	SNS prompt		
CsI[Na]	69.2 [5.0]	70.2 [5.1]	89.6 [6.4]
HPGe	25.9 [5.1]	26.2 [5.2]	33.5 [6.6]
LAr	14.7 [2.9]	14.9 [2.9]	19.1 [3.7]
NaI[Tl]	16.6 [2.8]	16.8 [2.8]	21.5 [3.6]
	SNS delayed		
CsI[Na]	54.5 [4.2]	48.7 [3.7]	49.8 [3.7]
HPGe	21.3 [4.2]	18.9 [3.8]	19.1 [3.8]
LAr	11.3 [2.3]	10.1 [2.1]	10.4 [2.1]
NaI[Tl]	10.0 [2.3]	9.1 [2.0]	9.4 [2.0]
	Reactor		
CONUS	1.9 [0.37]	1.3 [0.26]	1.1 [0.22]
CONNIE	0.90 [0.13]	0.63 [0.09]	0.53 [0.08]
MINER	1.7 [0.58]	1.2 [0.41]	1.0 [0.34]
TEXONO	3.2 [0.46]	2.3 [0.32]	1.9 [0.27]
RED100	1.0 [0.14]	0.72 [0.10]	0.61 [0.08]
	Solar		
Borexino	0.44	0.36	0.28

90% C.L. limits on TMM elements $|\Lambda_i|$, in units of 10^{-10} μ_B, from current and future CEνNS experiments. The numbers in square brackets indicate the attainable sensitivities in the future setups.

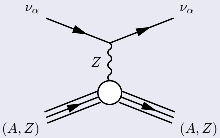
- CEνNS experiments are sensitive to EM neutrino properties
- can probe TMMs at $10^{-11}\mu_B$ at least
- competitive with large-scale solar neutrino experiments

Miranda, DKP, Tórtola, Valle, arXiv:1905.03750

Outlook

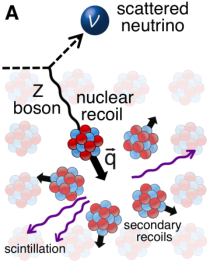
SM CEνNS reaction (conventional)

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



- Conventional, well-studied ν-process theoretically
- Finally observed by COHERENT in August 2017, CONUS (hints)
  (other: MINER, TEXONO, CONNIE, Ricochet, νGEN, ν-cleus etc.)
- Very high experimental sensitivity (low detector threshold) is required

- irreducible background for direct dark matter experiments: *neutrino-floor*
- can probe nuclear form factors
- **any deviation from the SM would indicate a glimpse on new physics (NSIs, EM properties, novel mediators)** ✓
- competitive determination of $\sin^2\theta_W$ at low-energy
- valuable tool for sterile oscillation searches
- important in supernova dynamics (investigate deep sky)
- study g_A quenching of electroweak interactions



Thank you for your attention !

Extras

Evaluation of the form factors (Helm)

Convolution of two nucleonic densities, one being a uniform density with cut-off radius R_0, (namely box or diffraction radius) characterizing the interior density and a second one that is associated with a Gaussian falloff in terms of the surface thickness s.

$$F_{\rm Helm}(Q^2) = F_B F_G = 3\frac{j_1(QR_0)}{qR_0}\, e^{-(Qs)^2/2}$$

The first three moments

$$\langle R_n^2 \rangle = \frac{3}{5}R_0^2 + 3s^2$$
$$\langle R_n^4 \rangle = \frac{3}{7}R_0^4 + 6R_0^2 s^2 + 15s^4$$
$$\langle R_n^6 \rangle = \frac{1}{3}R_0^6 + 9R_0^4 s^2 + 63R_0^2 s^4 + 105s^6\,.$$

- $j_1(x)$ is the known first-order Spherical-Bessel function
- box or diffraction radius R_0 (interior density)
- $s = 0.9$ fm: surface thickness of the nucleus from spectroscopy data (Gaussian fallof).

J. Engel, Phys.Lett. **B 264** (1991) 114

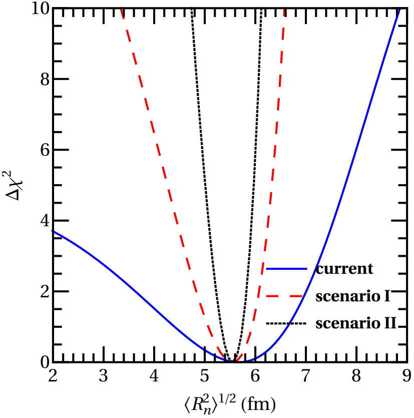
Evaluation of the form factors (Klein-Nystrand)

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.

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

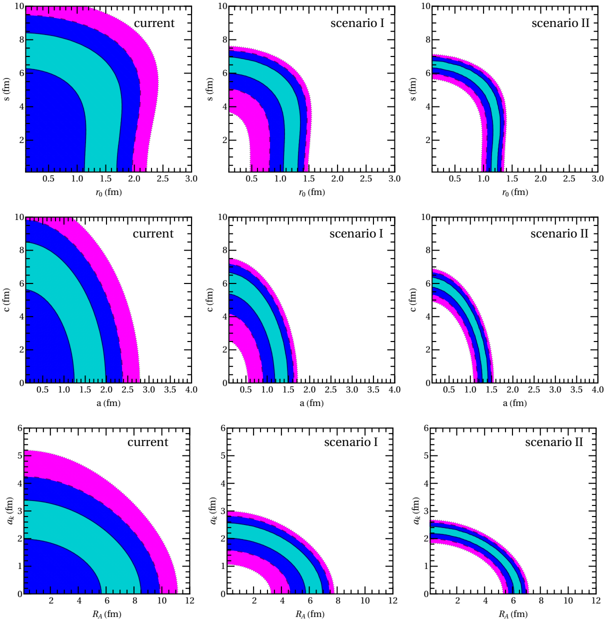
The rms radius is: $\langle R^2 \rangle_{\mathrm{KN}} = 3/5 R_A^2 + 6a_k^2$

S. Klein and J. Nystrand, Phys.Rev. C60 (1999) 014903



Papoulias et al. arXiv:1903.03722

Probing nuclear form factors: COHERENT exp.



Papoulias et al. arXiv:1903.03722