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COHERENT constraints on generalised neutrino-quark interactions

2018 TeV Particle Astrophysics conference (TeVPA 2018)
29 August 2018

Based on arXiv:1806.07424
with D. Aristizabal and N. Rojas

Coherent Elastic Neutrino-Nucleus Scattering

- NC (flavour-independent) process: $\nu + A \rightarrow \nu + A$

- CEνNS occurs when the neutrino energy E_ν is such that nucleon amplitudes sum up coherently (up to $E_\nu \sim 100$ MeV): cross section enhancement

- Total cross section scales approximately like N^2

$$\frac{d\sigma}{dE_R} \propto N^2$$

- Can be few orders of magnitude larger than inverse beta decay process used to first observe neutrinos

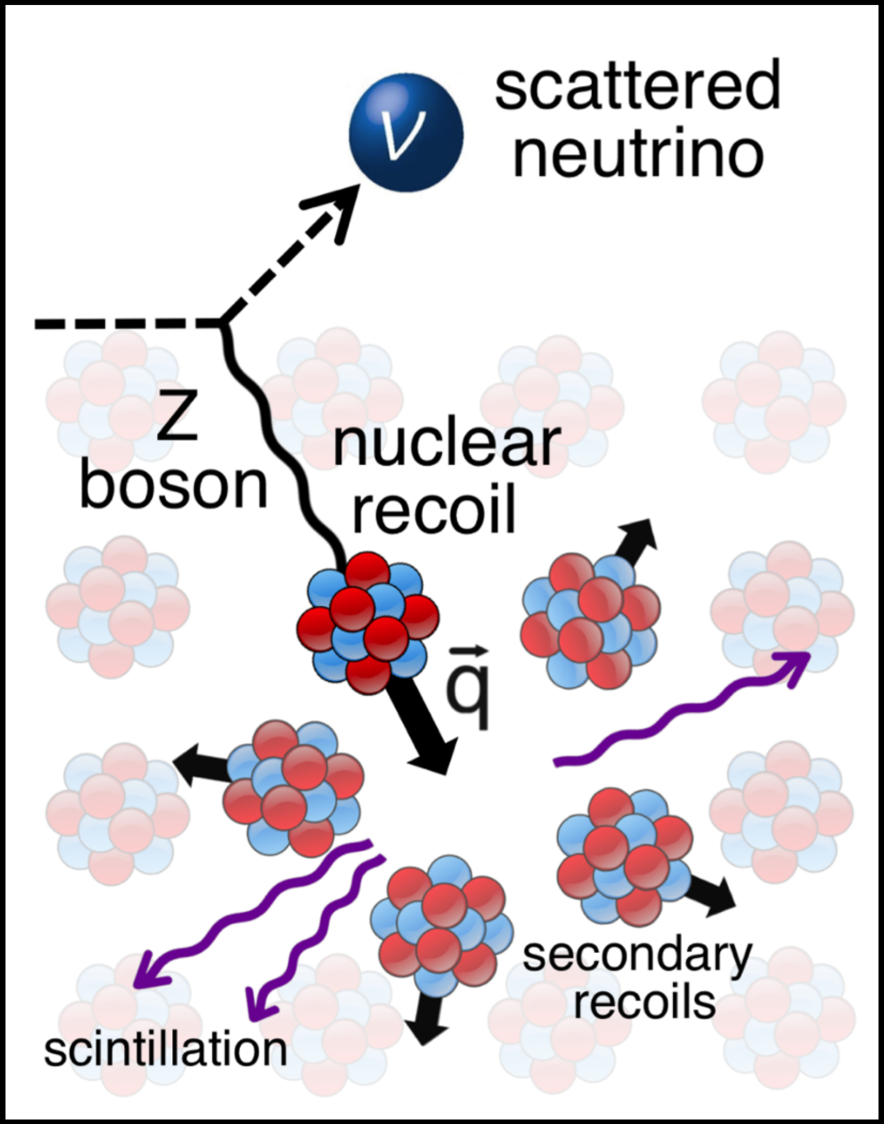


Image from COHERENT exp.

D.Z. Freedman, Phys. Rev. D 9 (1974)
V.B. Kopeliovich and L.L. Frankfurt, ZhETF Pis. Red. 19 (1974)

Coherent Elastic Neutrino-Nucleus Scattering

- Well-calculable cross-section in SM, $\frac{d\sigma}{dE_R} = \frac{G_F^2}{4\pi} m_N Q_{\rm SM}^2 \left(1 - \frac{E_R m_N}{2E_\nu^2}\right) F^2(q^2)$

$Q_{SM} \sim N^2$

- CEνNS is an exceptionally challenging process to observe
- Despite its large cross section, not observed for years due to tiny nuclear recoil energies
- Heavier nuclei: higher cross section but lower recoil
- Both cross-section and maximum recoil energy increase with neutrino energy
- Max recoil energy: $E_R^{\rm max} = \frac{2E_\nu}{m_N}$
- Related to dark matter direct detection experiments
- CEνNS from natural neutrinos creates ultimate background for direct DM search experiments

D.Z. Freedman, Phys. Rev. D 9 (1974)

M.W. Goodman, E. Witten, Phys Rev D 31 (1985)

Billard et al., Phys. Rev. D89 (2014) 023524

The COHERENT experiment

- COHERENT collaboration observed CEνNS at a 6.7-sigma confidence level in 2017 (more than 40 years after its prediction)
- Uses intense neutrino source provided by Spallation Neutron Source (SNS) at Oak Ridge National Laboratory
- (~1 GeV) Pulsed protons hit a liquid mercury fixed target
- Neutrinos stem from the decays of stopped pions and muons resulting in flux with well-defined spectral and timing characteristics

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$ monochromatic, prompt

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

- The COHERENT detector uses different nuclear targets to allow for measurement of characteristic N^2 cross-section dependence
- Consists of 14.6 kg of CsI[Na]

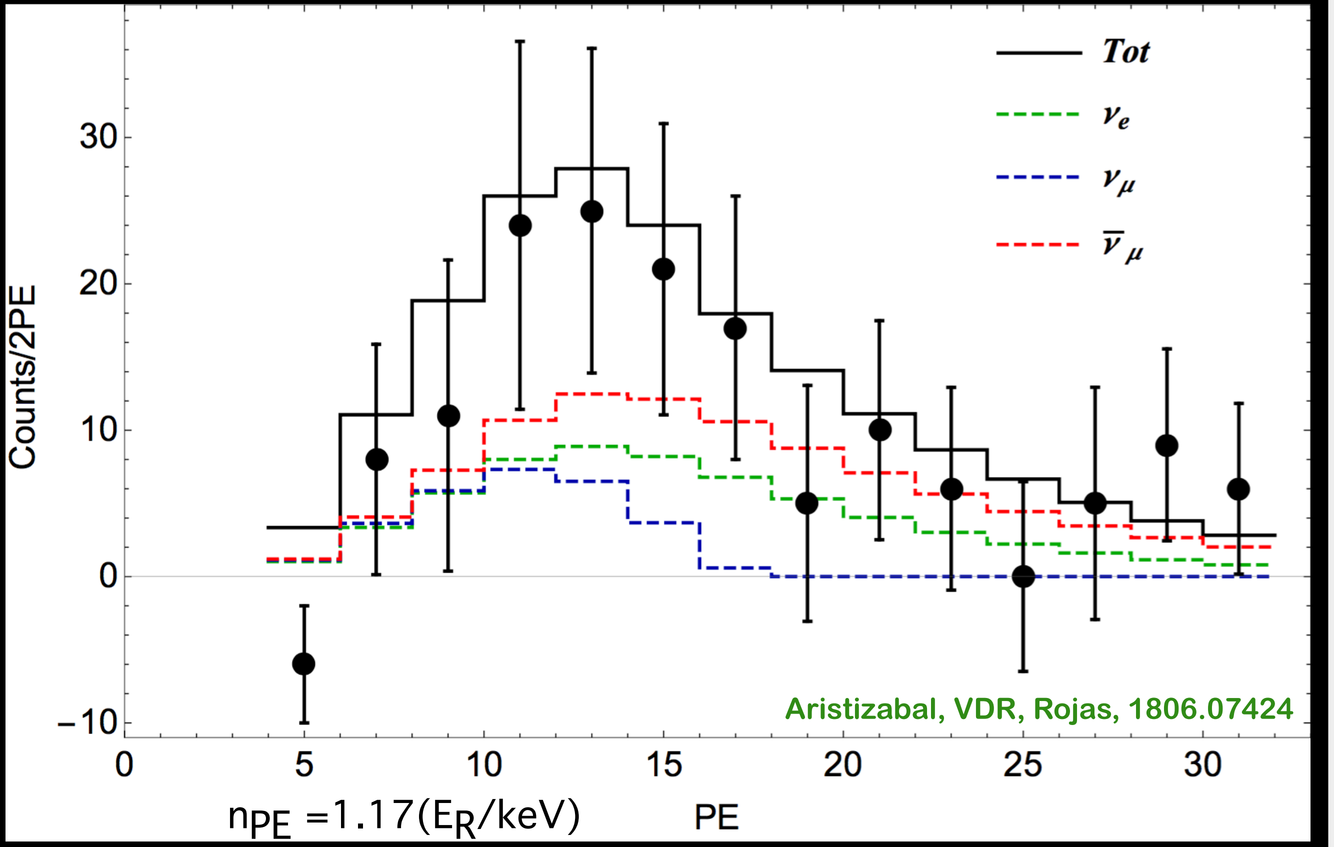
Akimov et al., Science (2017), 1708.01294

Asimov et. al, 1804.09459

K. Scholberg, Phys. Rev. D73 (2006) 033005

CEνNS physics potential

- CEvNS opens the window to a rich neutrino physics programme
  - Supernovae physics: determination of SN neutrino properties through measurement of the neutrino DSNB or neutrino emission in a single SN explosion
  - Nuclear properties such as: neutron form factor, neutron radius ...
  - Measurement, study and test of the SM axial nuclear current
  - Fundamental neutrino physics (weak mixing angle, effective neutrino charge radius and magnetic moment ...)
- New physics such as: non-standard neutrino interactions, sterile neutrinos, new NC heavy or light mediators ...
- COHERENT measurement consistent with SM at 1σ
- Still open room for new physics



D.Z. Freedman, Phys. Rev. D 9 (1974), C. Horowitz et al., Phys. Rev. D 68 (2003), H. Davoudiasl et al., Phys. Rev. D 89 (2014), J. Barranco et al., Phys. Rev. D 76 (2007), K. Patton et al., Phys. Rev. C 86 (2012), C. Horowitz & J. Piekarewicz, Phys. Rev. Lett. 86 (2000), K. Scholberg, Phys. Rev. D 73 (2006), P. Coloma et al., Phys. Rev. D 96 (2017), A.J. Anderson et al., Phys. Rev. D 86 (2012), Coloma et al. Phys. Rev. D 96, 115007, Cadeddu et al Phys. Rev. Lett. 120, 072501, Liao and Marfatia Phys. Lett. B775 (2017) 54–57, Papoulias and Kosmas Phys. Rev. D97 (2018) 033003, Farzan et al. JHEP 05 (2018) 066, ...

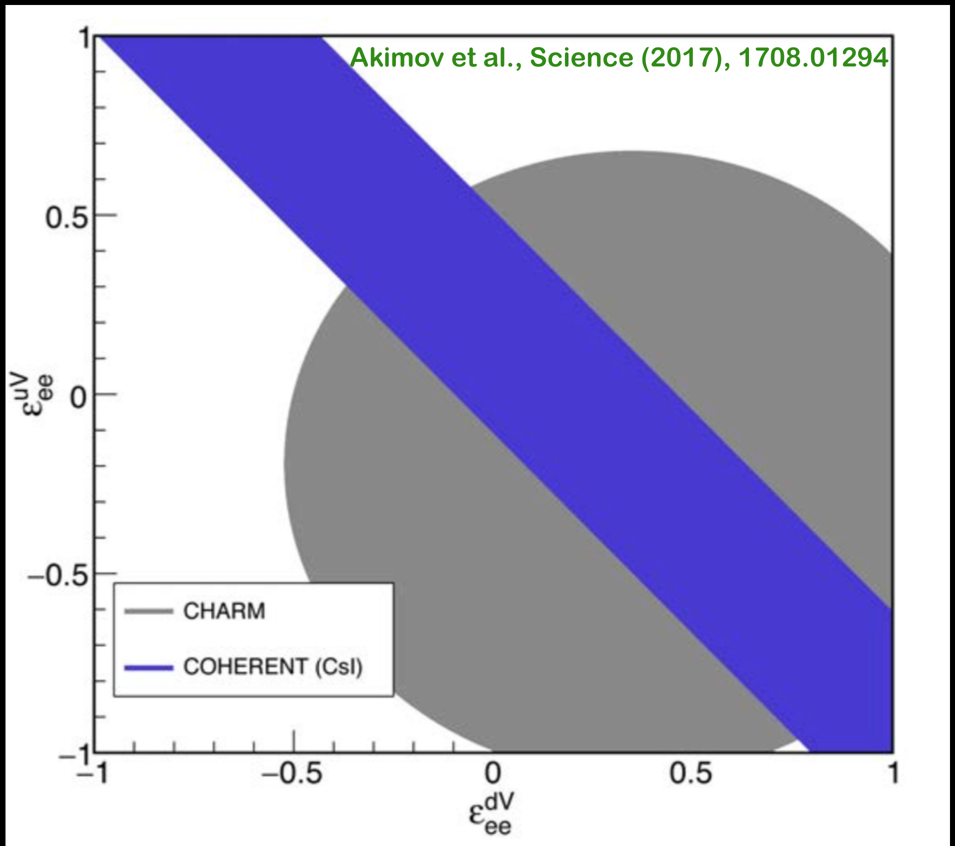
CEνNS and new physics interactions

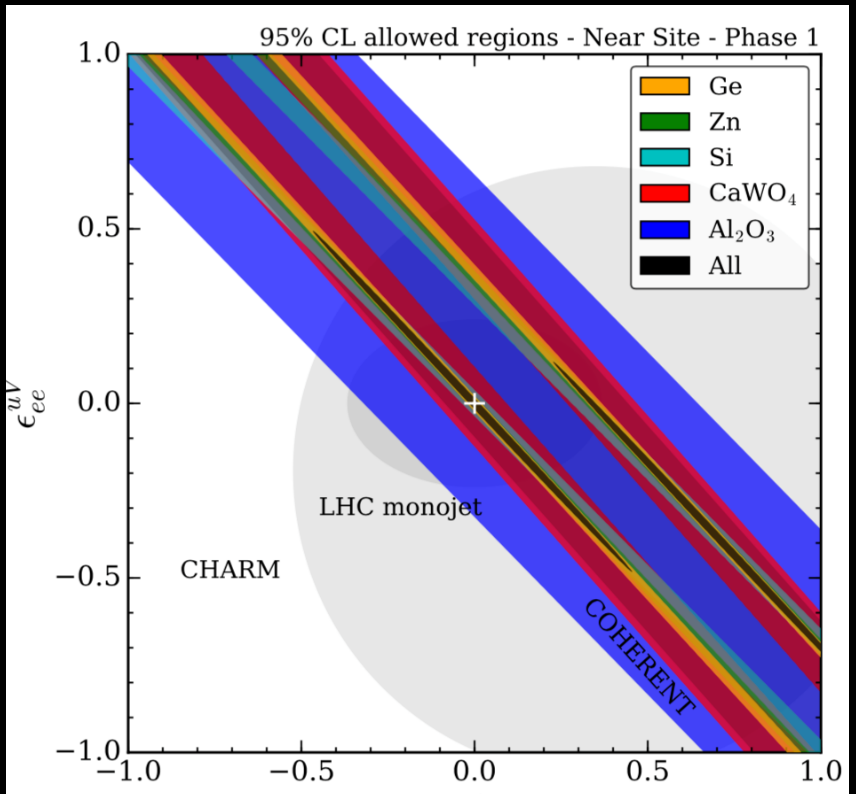
- Neutrino NSI: non-standard interactions parametrised in a model-independent and phenomenological way

$$\mathcal{L} \sim G_F \sum_{q=u,d} \bar{\nu}_i (1-\gamma_5)\gamma_\mu \nu_j \bar{q}(\epsilon^{qV}_{ij} - \epsilon^{qA}_{ij}\gamma_5)\gamma^\mu q$$

- Pheno constraints from forward coherent scattering (matter potentials), DIS and oscillation data, LHC mono jet ...
- For light mediators (mX ≲ 1 GeV) contributions of NSI to DIS are suppressed, COHERENT constraints are important

Coloma et al. Phys. Rev. D 96, 115007, Gonzalez-Garcia et al. 1803.03650





Billard et al. 1805.01798

Neutrino Generalised Interactions (NGI)

- NSI are a subset of a larger set of neutrino-quark interactions: Neutrino Generalized Interactions (NGI)
- all Lorentz invariant non-derivative interactions of neutrinos with first generation quarks

$$\mathscr{L}_{\mathrm{eff}}^{\mathrm{NGI}} = \frac{G_F}{\sqrt{2}} \sum_X \bar{\nu}\Gamma^X \nu \, \bar{q}\Gamma_X \left(C_X^q + i\gamma_5 \, D_X^q\right) q$$

$$\Gamma_X = \{\mathbb{1}, i\gamma_5, \gamma_\mu, \gamma_5\gamma_\mu, \sigma_{\mu\nu}\}$$

Kayser et al. Phys. Rev. D 20, 87
Lindner et al. JHEP03(2017)097

- Diagonal and non-diagonal Lorentz structures
- Constrain dominant spin-independent contributions (C_X^q)
- Neglect Pseudoscalar and Axial interactions (spin-dependent: $Z_\uparrow - Z_\downarrow$, $N_\uparrow - N_\downarrow$)

Freedman et al. Ann. Rev. Nucl. Part. Sci. 27 (1977)

$$\mathscr{L}_S \sim (\bar{\nu}\nu)\left[\bar{q}\left(C_S^q + i\gamma_5 \cancel{D_S^q}\right) q\right]$$

$$\mathscr{L}_P \sim (\bar{\nu}\gamma_5\nu)\left[\bar{q}\left(\gamma_5 \cancel{C_P^q} + i D_P^q\right) q\right]$$

$$\mathscr{L}_V \sim (\bar{\nu}\gamma^\mu\nu)\left[\bar{q}\left(\gamma_\mu C_V^q + i\gamma_\mu\gamma_5 \cancel{D_V^q}\right) q\right]$$

$$\mathscr{L}_A \sim (\bar{\nu}\gamma^\mu\gamma_5\nu)\left[\bar{q}\left(\gamma_\mu\gamma_5 \cancel{C_A^q} + i\gamma_\mu D_A^q\right) q\right]$$

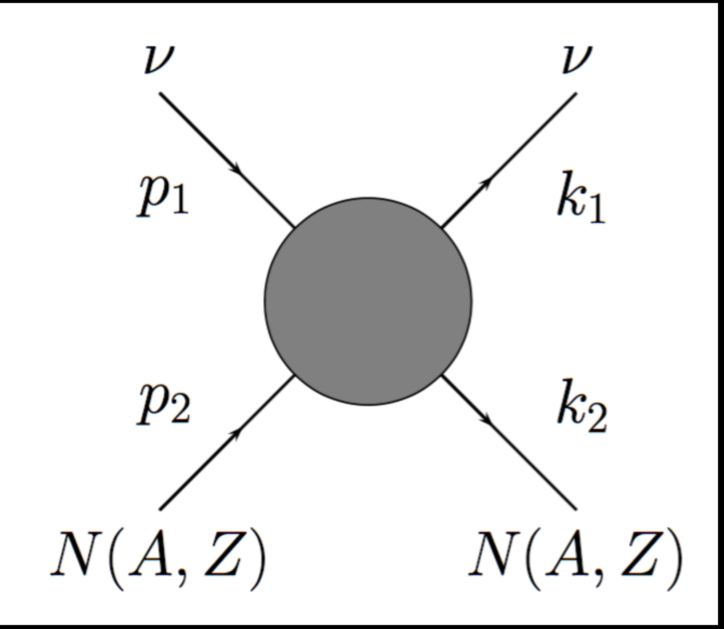
$$\mathscr{L}_T \sim (\bar{\nu}\sigma^{\mu\nu}\nu)\left[\bar{q}\left(\sigma_{\mu\nu} C_T^q + i\sigma_{\mu\nu}\gamma_5 \cancel{D_T^q}\right) q\right]$$

Neutrino Generalised Interactions (NGI)

- Constraints on NGI (apart from V) arise only from scattering processes (order G_F^2 interactions)
- Cross section parameterised in terms of nuclear currents: Scalar, Vector and Tensor

$$\frac{d\sigma^a(q^2=0)}{dE_r} = \frac{G_F^2}{4\pi} m_{N_a} N_a^2 \left[\xi_S^2 \frac{E_r}{E_r^{\max}} + \xi_V^2 \left(1 - \frac{E_r}{E_r^{\max}} - \frac{E_r}{E_\nu}\right) + \xi_T^2 \left(1 - \frac{E_r}{2E_r^{\max}} - \frac{E_r}{E_\nu}\right) - R\frac{E_r}{E_\nu} \right]$$

$$E_r^{\max} \simeq 2E_\nu^2/m_{N_a}$$



- Single-parameter scenario
- Two-parameter scenario

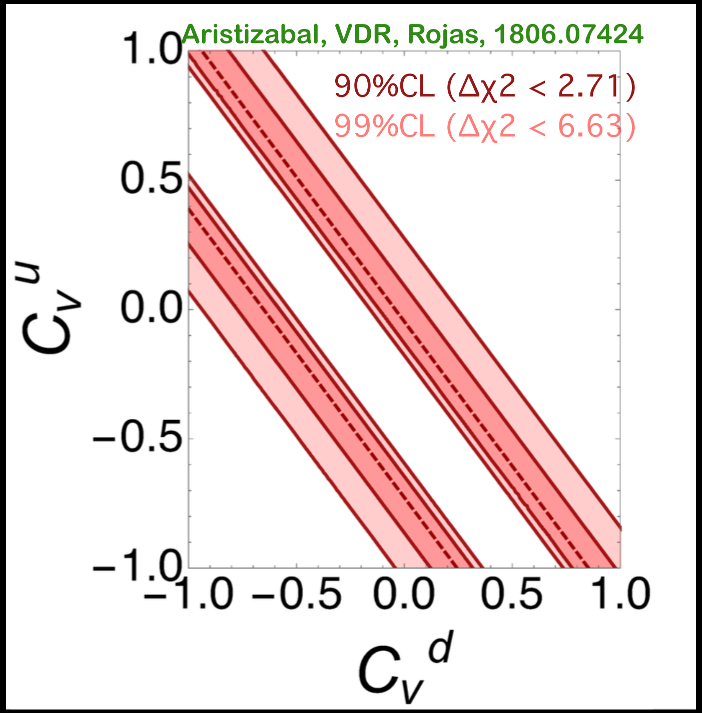
Lindner et al. JHEP03(2017)097
Aristizabal, VDR, Rojas, 1806.07424

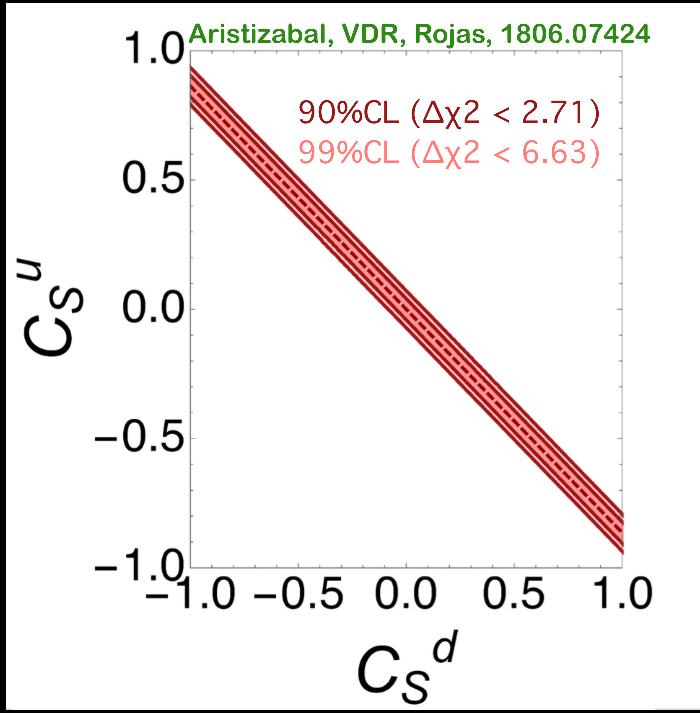
COHERENT constraints on NGI

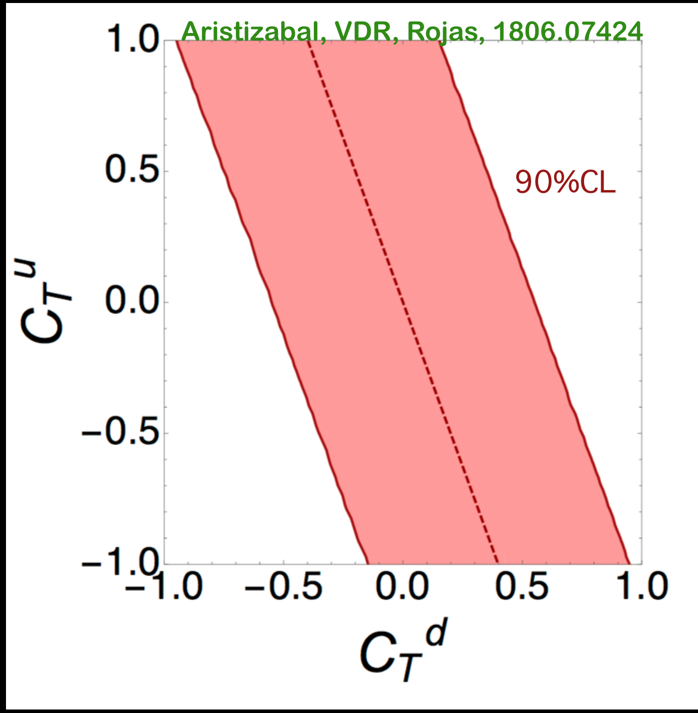
$$\chi^2 = \sum_{i=4}^{16} \left(\frac{N_i^{\text{meas}} - (1+\alpha) N_i^{\text{NGI}}(\mathscr{P}) - (1+\beta) B_i^{\text{on}}}{\sigma_i} \right)^2 + \left(\frac{\alpha}{\sigma_\alpha} \right)^2 + \left(\frac{\beta}{\sigma_\beta} \right)^2$$

- Single-parameter scenario
- Constraints on scalar-type interactions are the most stringent

Param	**BFP value**	90% CL	99% CL
ξ_S	0	$[-0.62, 0.62]$	$[-1.065, 1.065]$
ξ_V	-0.113	$[-0.324, 0.224]$	$[-0.436, 0.67]$
	-1.764	$[-2.102, -1.554]$	$[-2.545, -1.442]$
ξ_T	0	$[-0.591, 0.591]$	$[-1.071, 1.072]$

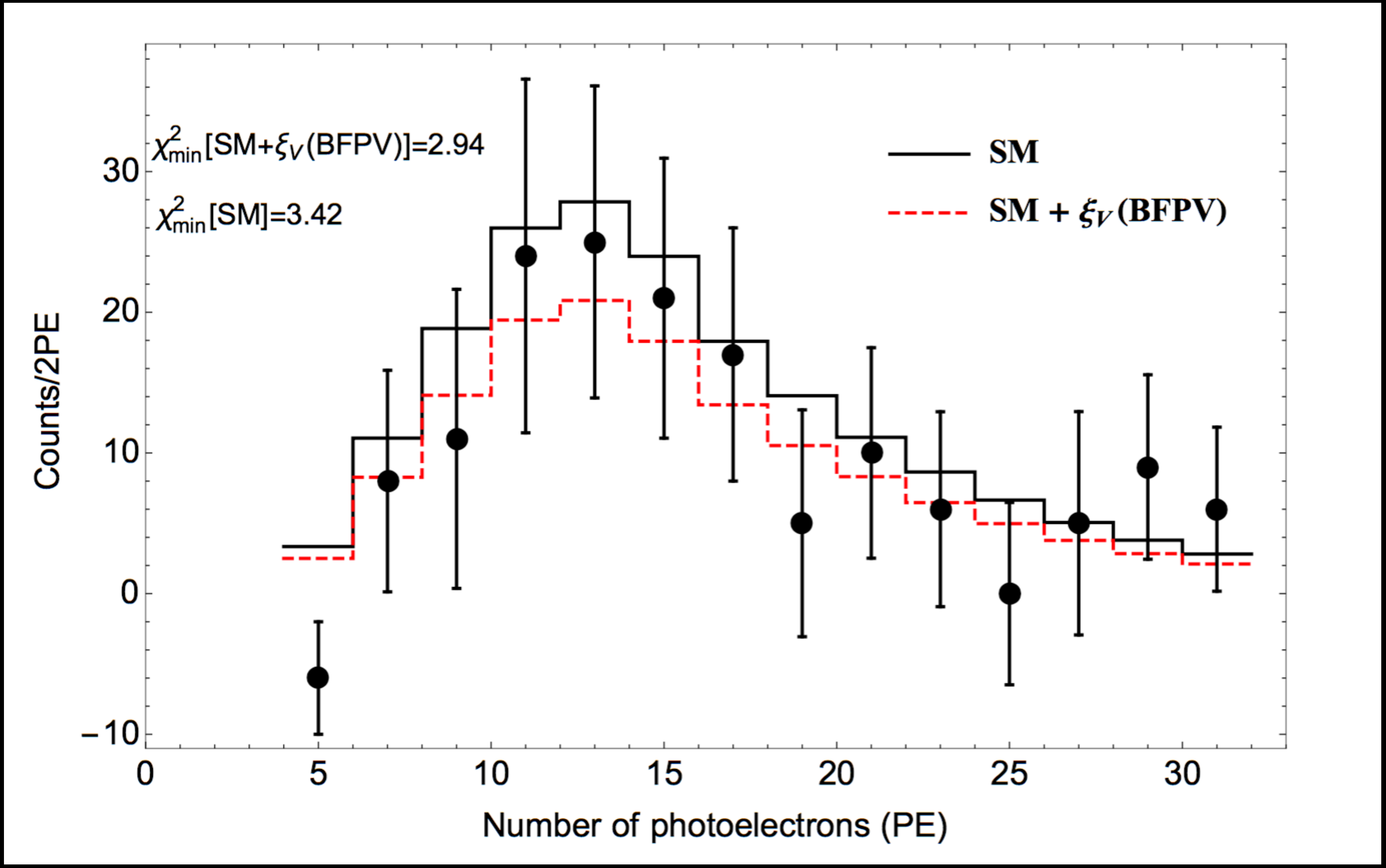






COHERENT constraints on NGI

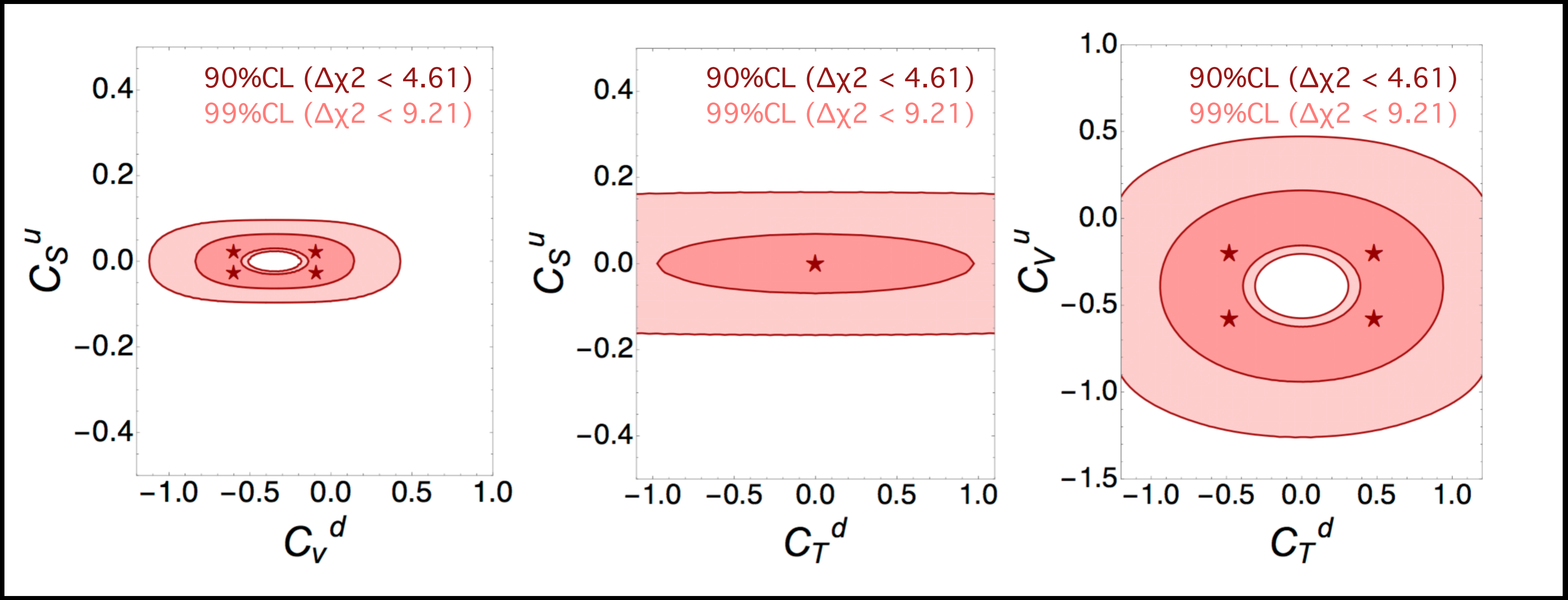
- Single-parameter scenario
- The presence of NGI can improve the data fit... In particular for vector interactions



$n_{PE} = 1.17(E_R/keV)$

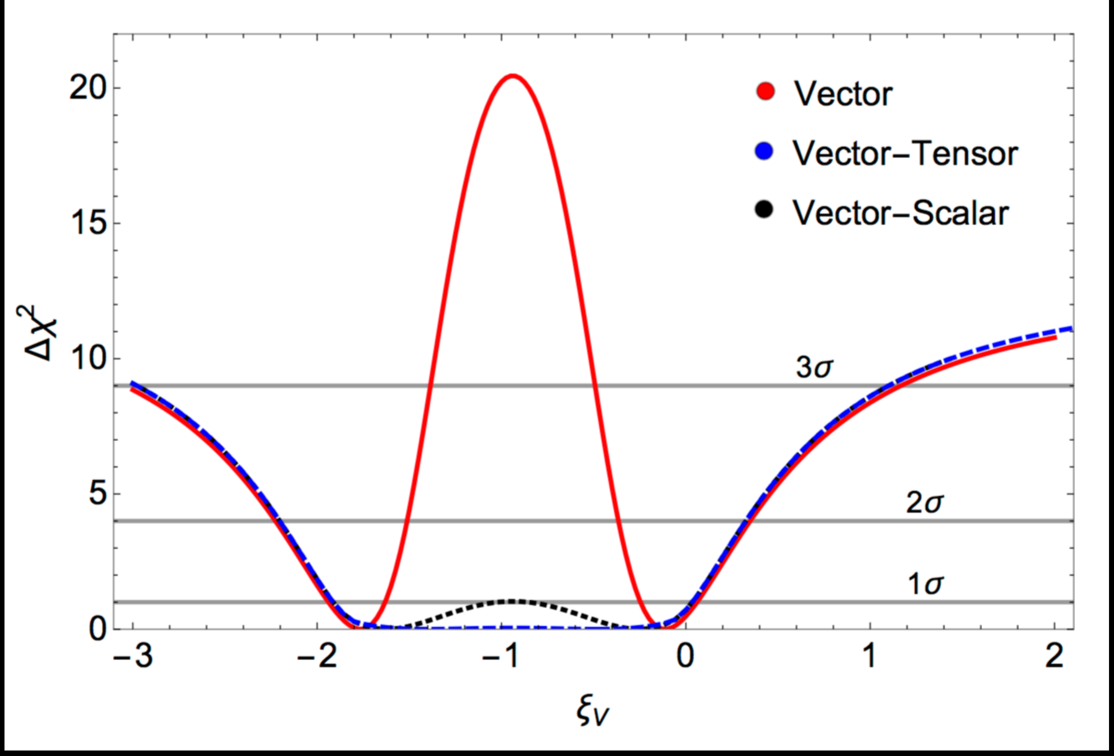
COHERENT constraints on NGI

- Two-parameter scenario



- The presence of an additional interaction at the nuclear level relaxes the bounds on the fundamental neutrino-quark couplings

$$\xi_V = -C_V = -[1 - (1 - 4\sin^2\theta_w) - N/Z] \simeq -0.95$$



Summary and outlook

- We have studied a generic set of effective Lorentz invariant non-derivative neutrino-quark interactions (NGI).
- We have employed the recent COHERENT data to place constraints on the different NGI effective parameters.
- In the single-parameter case, our findings show that the scalar interaction is the most constrained, with the tightest bound found for the Lorentz mixed pseudoscalar-scalar coupling. The presence of a vector NGI can slightly improve the COHERENT data fit.
- In the two-parameter case, we have found that the presence of an additional interaction at the nuclear level relaxes the bounds on the fundamental neutrino-quark couplings.
- CEvNS offers a plethora of physics opportunities. Future new COHERENT data and forthcoming data from CONUS and e.g. ν-CLEUS will allow unraveling the presence of new physics.

Summary and outlook

- We have studied a generic set of effective Lorentz invariant non-derivative neutrino-quark interactions (NGI).

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Thank you!

Backup

Future CEνNS experiments

- CONUS: 4-100 kg of germanium
- TEXONO: 1kg of germanium
- Connie: Si detector at Angra Reactor in Brasil
- RED100: Xe detector at Kalinin Reactor
- MINER: GeSi at a non-commercial Reactor NU-CLEUS

JHEP 1703 (2017) 097

Nucl.Instrum.Meth. A836 (2016) 67-82

JINST 11 (2016) P07024

JINST 12 (2017) C06018

Nucl.Instrum.Meth. A853 (2017) 53

Eur. Phys. J C77 (2017) 506

From quark to nuclear currents

- To compute the CEνNS cross section induced by the NGI we assume a fermion nuclear ground state with spin J = 1/2.

$$\frac{d\sigma^a(q^2=0)}{dE_r} = \frac{G_F^2}{4\pi} m_{N_a} N_a^2 \left[\xi_S^2 \frac{E_r}{E_r^{\max}} + \xi_V^2 \left(1 - \frac{E_r}{E_r^{\max}} - \frac{E_r}{E_\nu}\right) + \xi_T^2 \left(1 - \frac{E_r}{2E_r^{\max}} - \frac{E_r}{E_\nu}\right) - R \frac{E_r}{E_\nu} \right]$$

- STEP I: $\mathcal{O}_q \xrightarrow{\text{step (I)}} \mathcal{O}_n$ we calculate quark currents in nucleons according to

e.g. Dent et al. Phys. Rev. D92 (2015) 063515

$$\langle n(p_f)|\bar{q}\,q|n(p_i)\rangle = \frac{m_n}{m_q} f_{T_q}\, \bar{n}\, n\,,$$
$$\langle n(p_f)|\bar{q}\gamma^\mu q|n(p_i)\rangle = \mathcal{N}_q^n\, \bar{n}\,\gamma^\mu\, n\,,$$
$$\langle n(p_f)|\bar{q}\,\sigma^{\mu\nu}\, q|n(p_i)\rangle = \delta_q^n\, \bar{n}\,\sigma^{\mu\nu}\, n\,.$$

- STEP II: $\mathcal{O}_n \xrightarrow{\text{step (II)}} \mathcal{O}_N$ we evaluate the correlators of nucleonic currents in nuclei, which involve nuclear form factors:

$$\langle N(k_2)|\bar{n}\,n|N(p_2)\rangle = \bar{N}\,N F(q^2)$$

Helm form factor

$$\langle N(k_2)|\bar{n}\gamma^\mu n|N(p_2)\rangle = \bar{N}\left(\gamma^\mu F(q^2) + \frac{\sigma^{\mu\nu} q_\nu}{2m_N} F_1(q^2)\right) N$$

$$\langle N(k_2)|\bar{n}\,\sigma^{\mu\nu}\, n|N(p_2)\rangle = \bar{N}\left(i\sigma^{\mu\nu} F(q^2) - \frac{\gamma^\mu q^\nu - \gamma^\nu q^\mu}{2m_N} F_2(q^2) - \frac{K^\mu q^\nu - K^\nu q^\mu}{2m_N^2} F_3(q^2)\right) N$$

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$$\xi_S^2 = \frac{C_S^2 + D_P^2}{N^2}\,, \quad \xi_V^2 = \frac{C_V^2 + D_A^2}{N^2}\,, \quad \xi_T^2 = 8\frac{C_T^2}{N^2}\,, \quad R = 2\frac{C_S C_T}{N^2}$$

- ν – N coefficients are written as follows

$$C_S = Z \sum_{q=u,d} C_S^{(q)} \frac{m_p}{m_q} f_{T_q}^p + (A-Z) \sum_{q=u,d} C_S^{(q)} \frac{m_n}{m_q} f_{T_q}^n \,,$$

$$C_V = Z\left(2C_V^u + C_V^d\right) + (A-Z)\left(C_V^u + 2C_V^d\right) \,,$$

$$C_T = Z\left(\delta_u^p C_T^u + \delta_d^p C_T^d\right) + (A-Z)\left(\delta_u^n C_T^u + \delta_d^n C_T^d\right) \,.$$

e.g. Dent et al. Phys. Rev. D92 (2015) 063515

Outline

1) Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)

- CEνNS
- The COHERENT experiment
- CEνNS physics potential
- CEνNS and new physics interactions

2) Neutrino generalised interactions (NGI)

3) COHERENT constraints on NGI

- One-parameter analysis
- Two-parameter analysis