Valentina De Romeri
(IFIC Valencia - UV/CSIC)

CP violating effects in coherent elastic neutrino-nucleus scattering processes

DESY THEORY WORKSHOP
Quantum field theory meets gravity
24-27 September 2019, DESY Hamburg

Based on JHEP 1909 (2019) 069 in collaboration 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

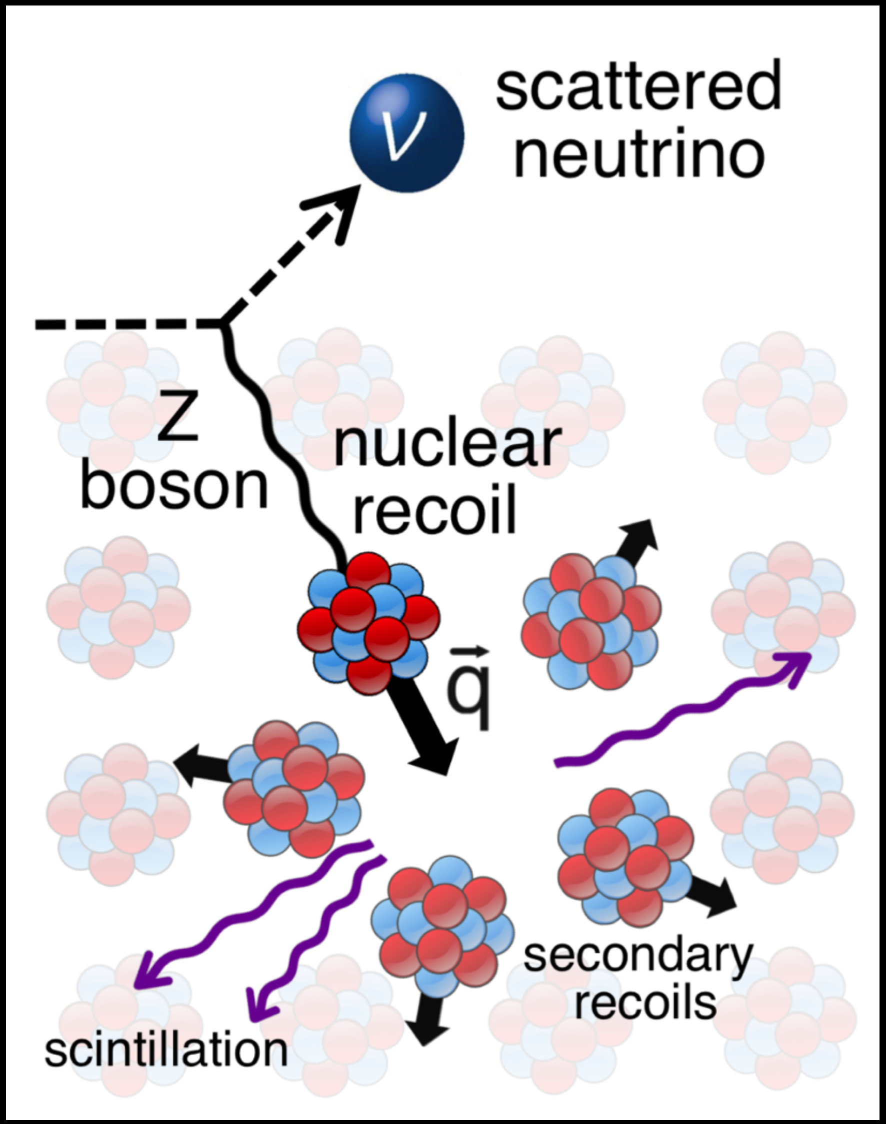


Image from COHERENT exp.

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

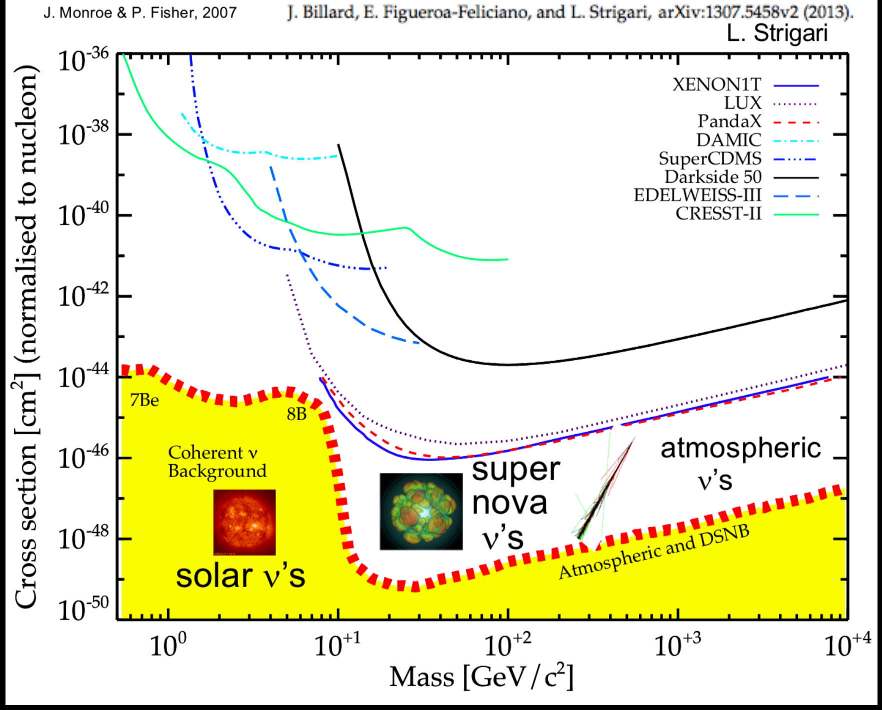
- Well-calculable cross-section in SM, $Q_{SM} \sim N^2$

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

- 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

CEνNS status

From stopped pions:

- The COHERENT collaboration at Oak Ridge National Laboratory observed CEνNS at a 6.7-sigma confidence level in 2017 (more than 40 years after its prediction).

- The COHERENT detector uses different nuclear targets to allow for measurement of characteristic N^2 cross-section dependence
- Recent result from LAr: <7.4 observed CEvNS events

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)	Data-taking start date	Future
CsI[Na]	Scintillating crystal	14.6	20	6.5	9/2015	Decommissioned
Ge	HPGe PPC	16	20	<few	2020	Funded by NSF MRI, in progress
LAr	Single-phase	22	20	20	12/2016, upgraded summer 2017	Expansion to **750 kg scale**
NaI[Tl]	Scintillating crystal	185*/ 3388	28	13	*high-threshold deployment summer 2016	Expansion to **3.3 tonne**, up to 9 tonnes

Image from K. Scholberg @ TAUP 2019

From nuclear reactors:

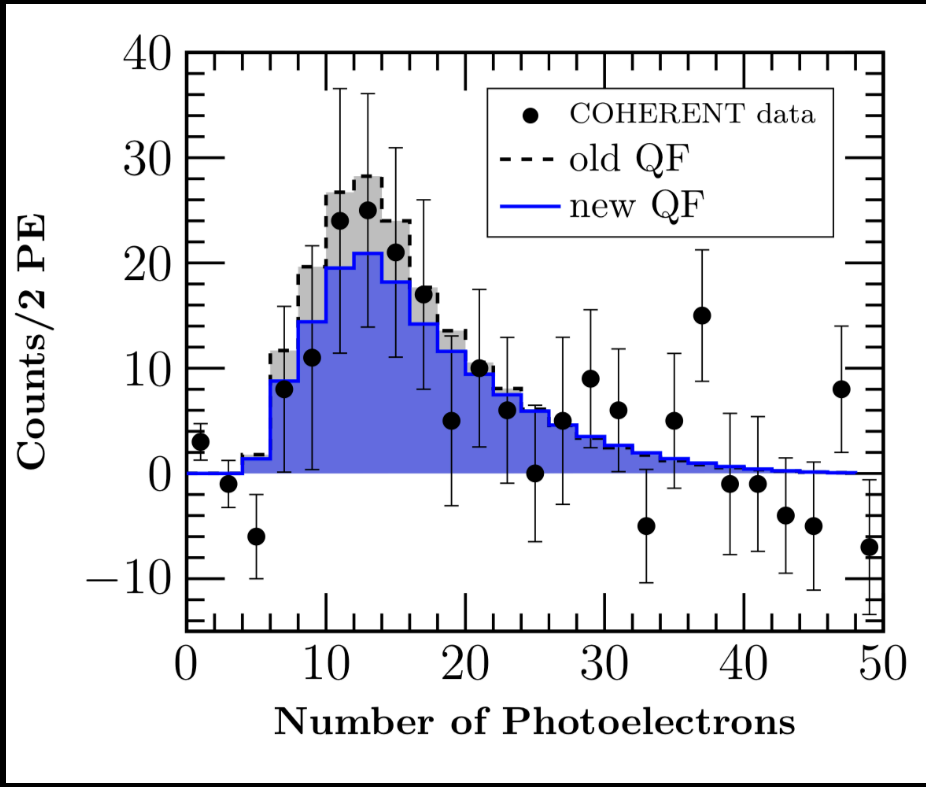
- Anti_ve are produced in fission reactions (single flavor); recoil energies<keV and backgrounds make it very challenging. E.g. CONUS, TEXONO, CONNIE, vCLEUS...
- CONNIE experiment measures low-energy recoils from CEvNS of reactor antineutrinos with silicon nuclei. It has not yet observed CEvNS at recoil energies below 20 keV.

Akimov et al., Science (2017), 1708.01294
Akimov et. al, 1804.09459
Akimov et al. 1909.05913
K. Scholberg, Phys. Rev. D73 (2006) 033005
Aguilar-Arevalo et al. 1906.02200

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



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

D. Papoulias, 1907.11644

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, Papoulias 2019, Cadeddu et al 2019, Giunti 2019, Khan et al. 2019...

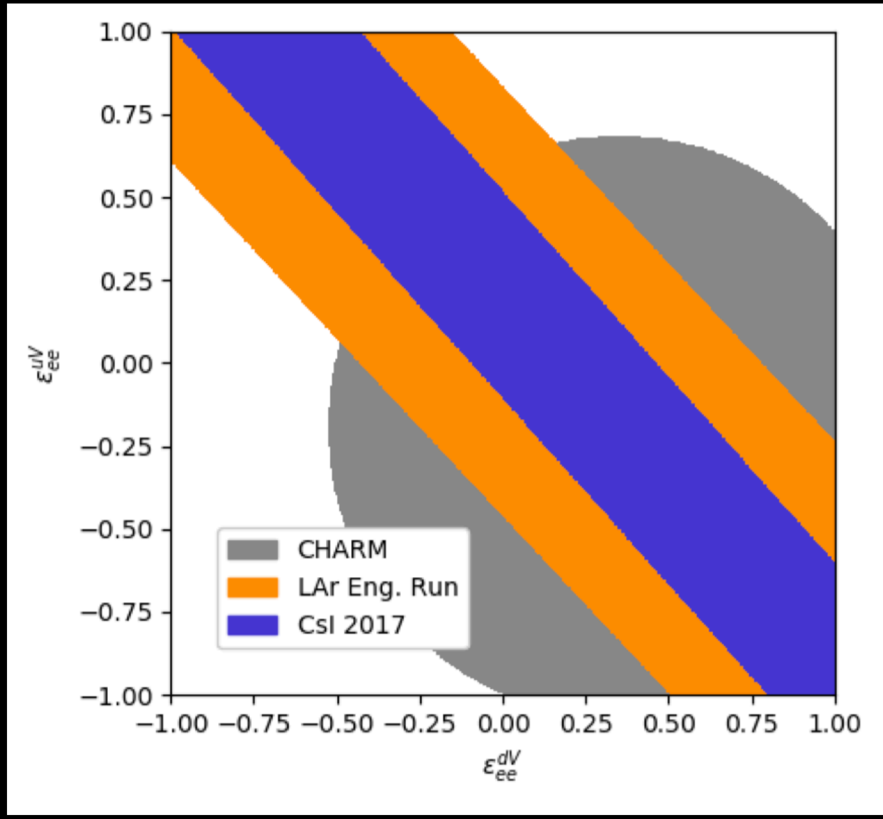
CEνNS and new physics interactions

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

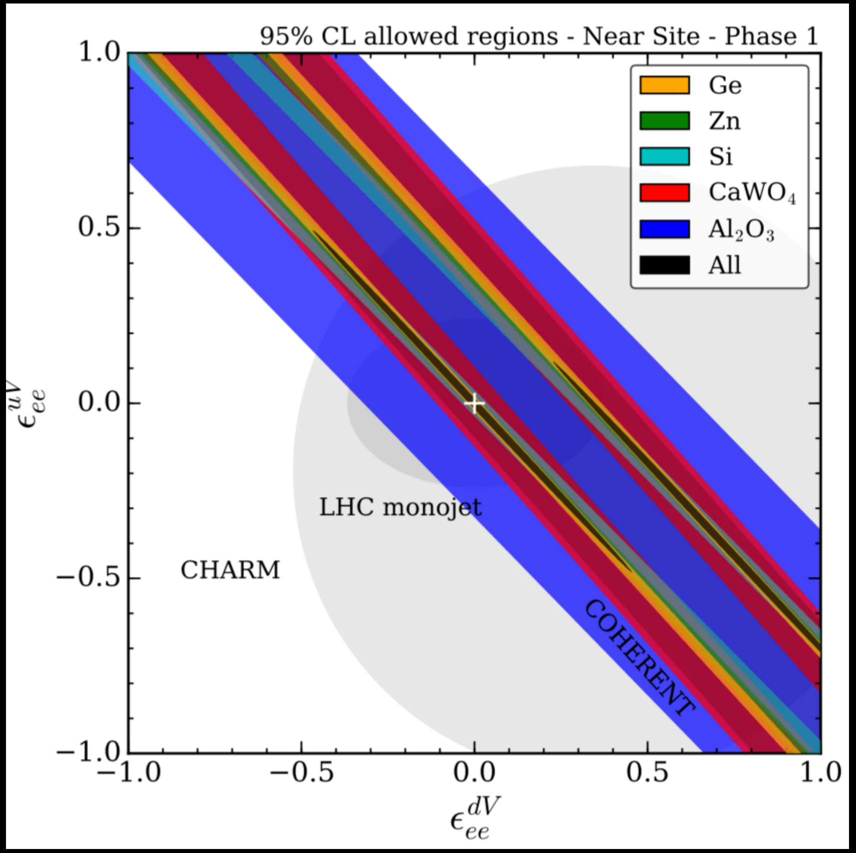
$$\mathcal{L} \sim G_F \sum_{q=u,d} \bar{\nu}_i (1-\gamma_5)\gamma_\mu \nu_j \bar{q}(\epsilon_{ij}^{qV} - \epsilon_{ij}^{qA}\gamma_5)\gamma^\mu q$$

- 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

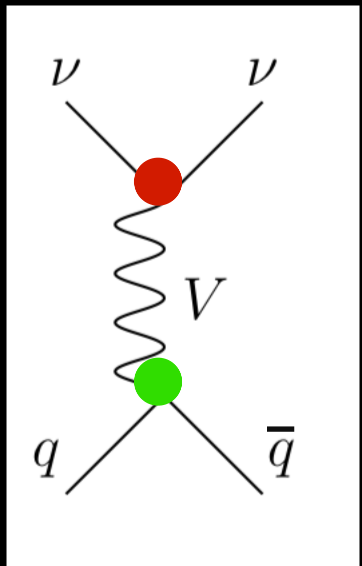


Akimov et al. 1909.05913



Billard et al. 1805.01798

CEνNS and light vector mediators with CPV



$$\mathcal{L} = \overline{\nu}\gamma_\mu(f_V + i f_A \gamma_5)\nu V^\mu + \sum_{q=u,d} h_V^q \overline{q}\gamma_\mu q V^\mu$$

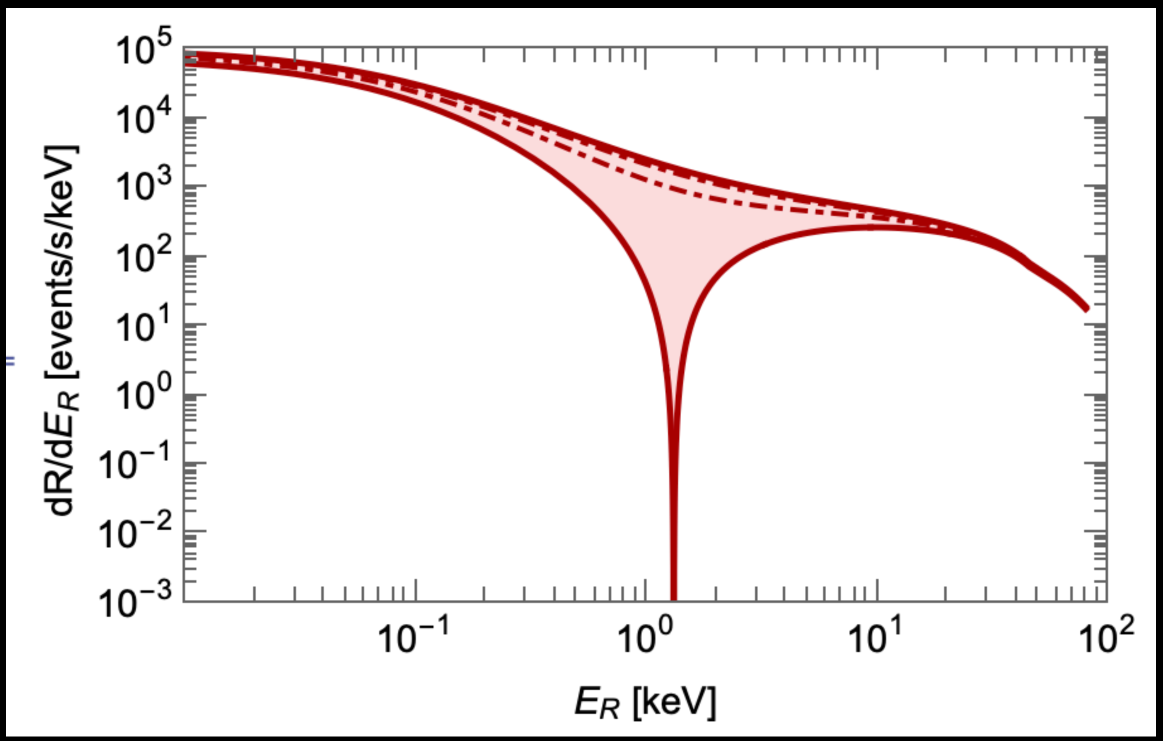
- Neutrino vector and axial currents
- Quark vector interactions (axial quark currents spin-suppressed effects)
- Universal flavour diagonal couplings

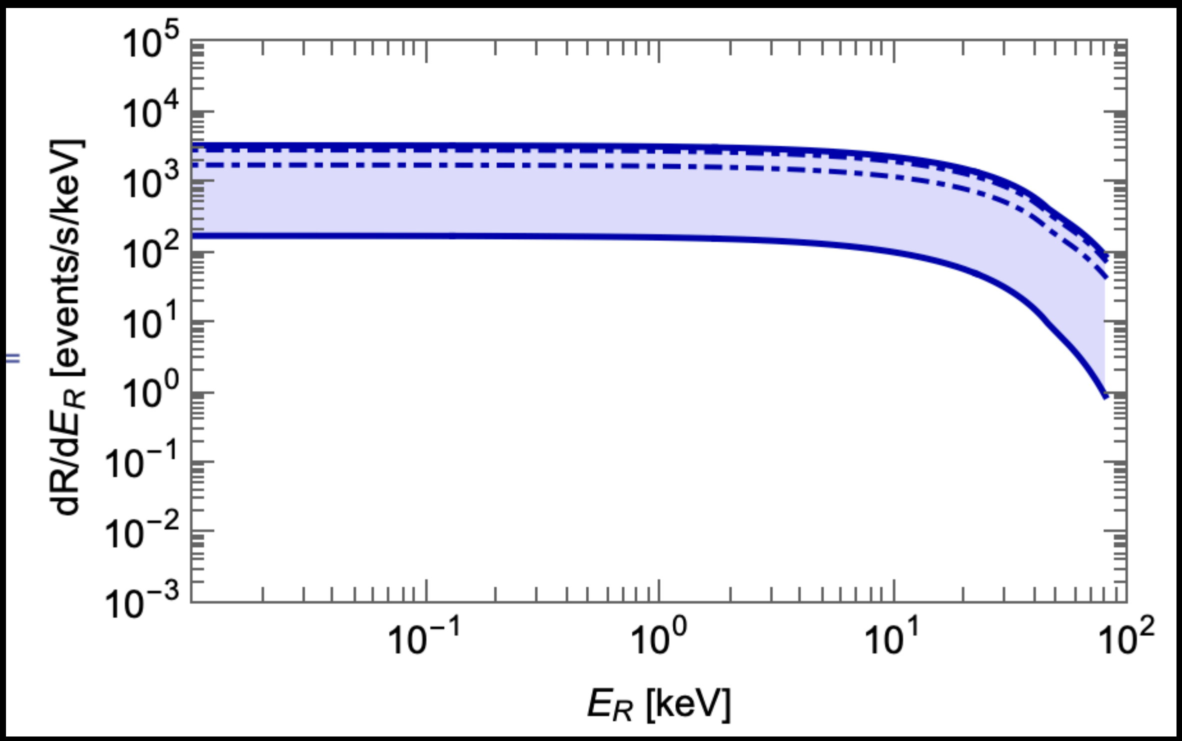
- Nine parameter problem: the vector boson mass, four moduli and four CP phases (fV, fA, hVq)

$$\frac{d\sigma}{dE_r} = \frac{G_F^2 m_i}{2\pi}\left|g_{SM}(q_i^2) - \overbrace{\boxed{\frac{h_V(q_i^2)(f_V - i f_A)}{\sqrt{2}G_F(q_i^2 - {m_V}^2)}}}^{|H_V|e^{i\phi}}\right|^2 \left(2 - \frac{E_r m_i}{E_\nu^2} - \frac{2E_r}{E_\nu} + \frac{E_r^2}{E_\nu^2}\right)$$

- g_{SM} is always negative: $\phi = 0$ produces destructive interference

Dip and no-dip regions





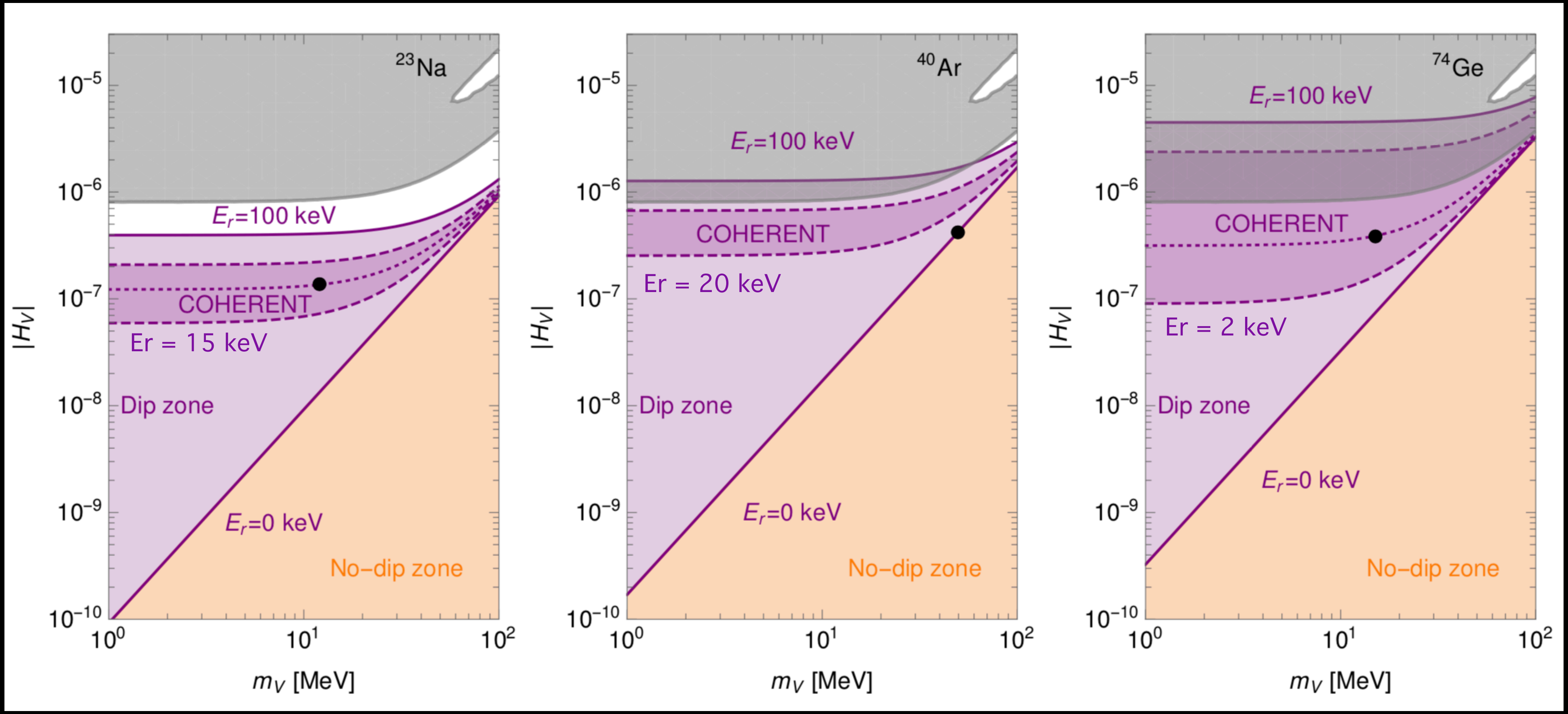
$$\frac{d\sigma}{dE_r} = \frac{G_F^2 m_i}{2\pi} \left| g_{SM}(q_i^2) - \frac{\overbrace{\boxed{h_V(q_i^2)(f_V - i f_A)}}^{|H_V|e^{i\phi}}}{\sqrt{2}G_F(q_i^2 - {m_V}^2)} \right|^2 \left(2 - \frac{E_r m_i}{E_\nu^2} - \frac{2E_r}{E_\nu} + \frac{E_r^2}{E_\nu^2}\right)$$

Analysis

- Perform the analysis in terms of H_V and ϕ.
- Reconstruction of full parameter space will imply large degeneracies (9 pars).
- For CP conserving parameters a full cancellation (exact in mono-target experiments) of the SM contribution is possible: dip at a given recoil energy at which the cancellation takes place.

- Boundary between dip and no-dip regions is determined by the condition:

$$|H_V| = -\sqrt{2} g_V G_F \left(2 m_i E_r + m_V^2\right)$$



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Effects of CP violation on CEvNS

The inclusion of CP violation has three main effects:

- Suppression of eventual dips in the event rate spectrum
- Degeneracy between the SM prediction and the light vector mediator signal (SM degeneracy)
- Degeneracy between spectra generated with real parameters and spectra including CP violating phases (real-vs-complex degeneracy).

Perform a χ^2 analysis to show how much ϕ can be constrained with experimental data.

Detector	Detector mass [kg]	Distance from source [m]	Threshold [keV]
Sodium	2000	28	15
Liquid Argon	1000	29	20
Germanium	15	22	2

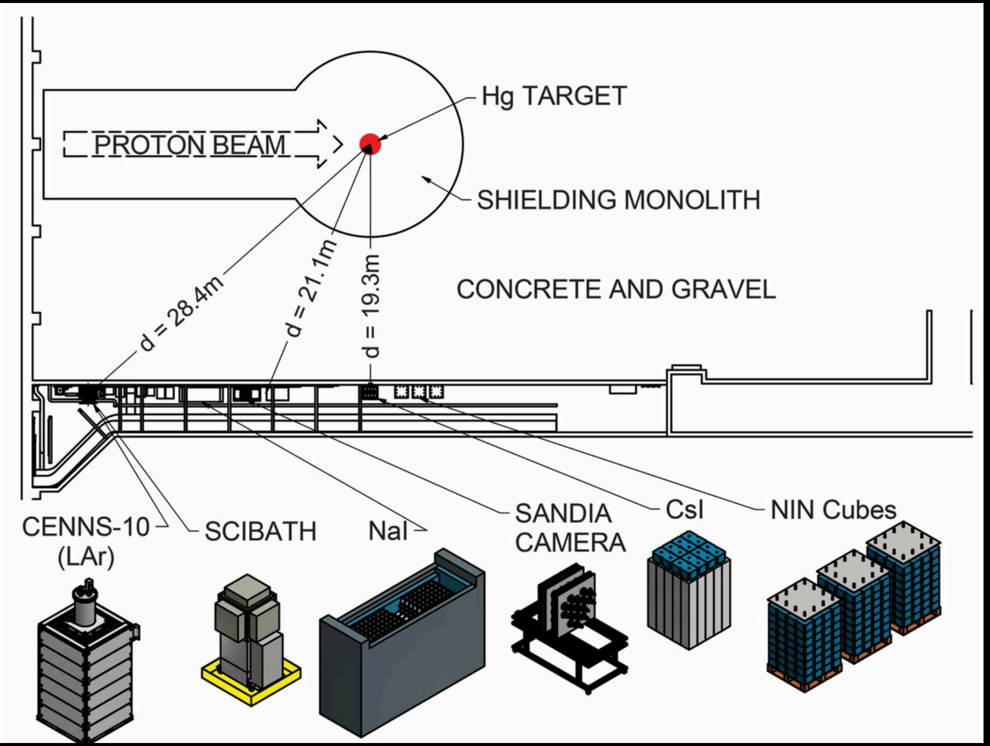
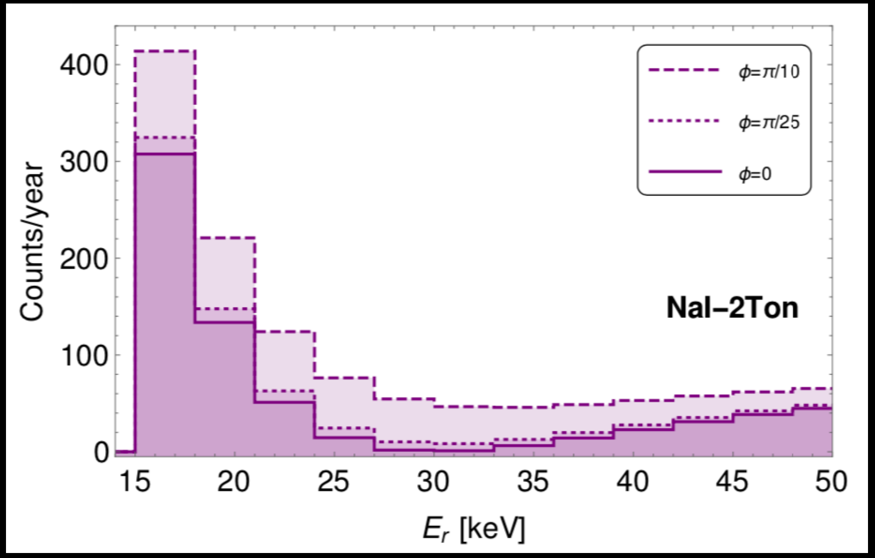
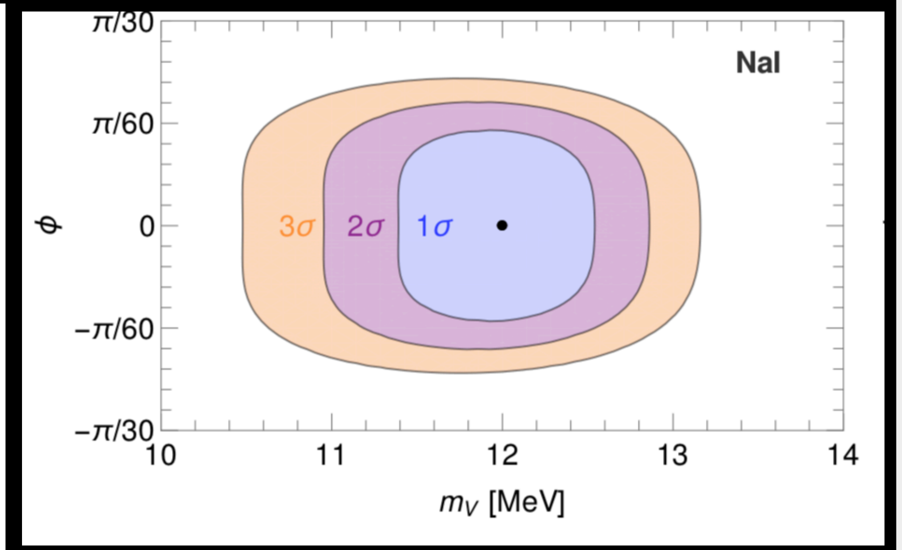


Fig. from Science Vol. 357, 6356, pp.1123

Dip region: the case of Na and Ge

Benchmark parameters for Na pseudo-experiment:
12 MeV, 1.32×10^{-7}, $\phi = 0$





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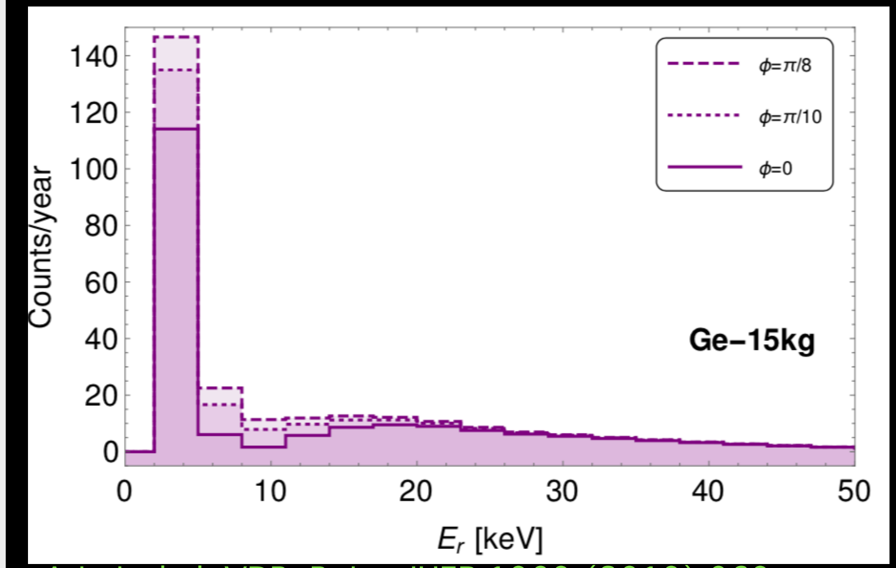
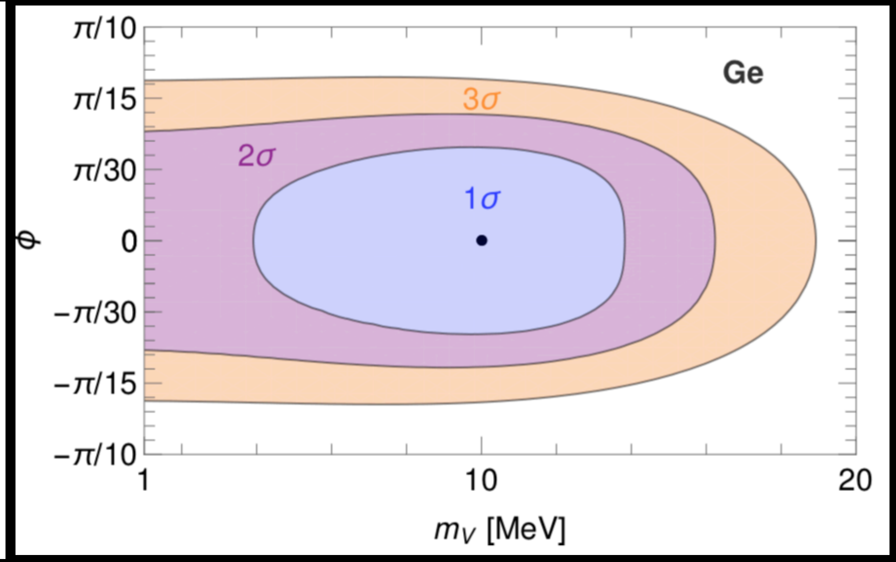
Effect of CP-violation: Suppression of eventual dip.
An observation of a dip in the event spectrum in the NaI detector cannot rule out CP violating interactions, but can place tight bounds on ϕ.





Benchmark parameters for Ge pseudo-experiment:
14 MeV, 4.17×10^{-7}, $\phi = 0$

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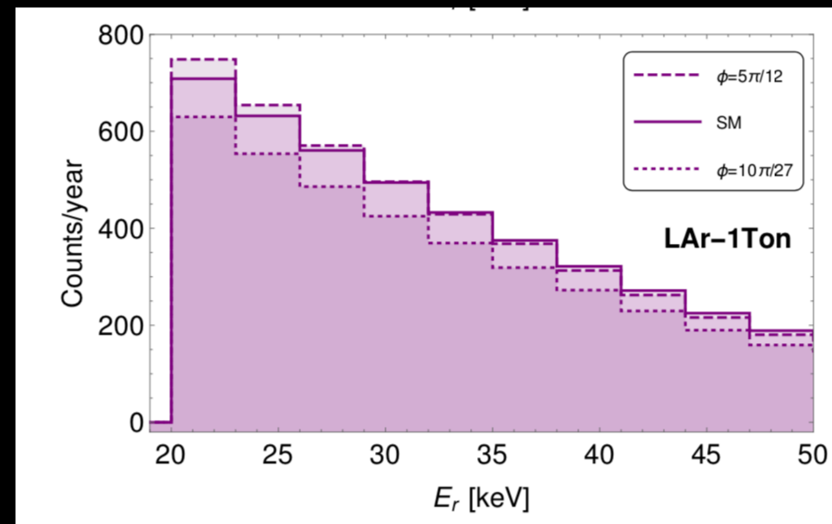
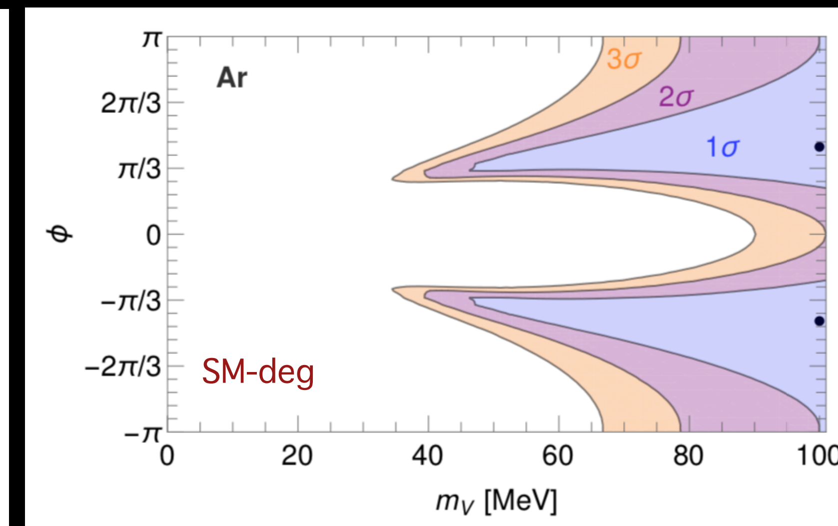
No-dip region: the case of LAr

Benchmark parameters for Ar SM-deg pseudo-experiment:
Hv = 0





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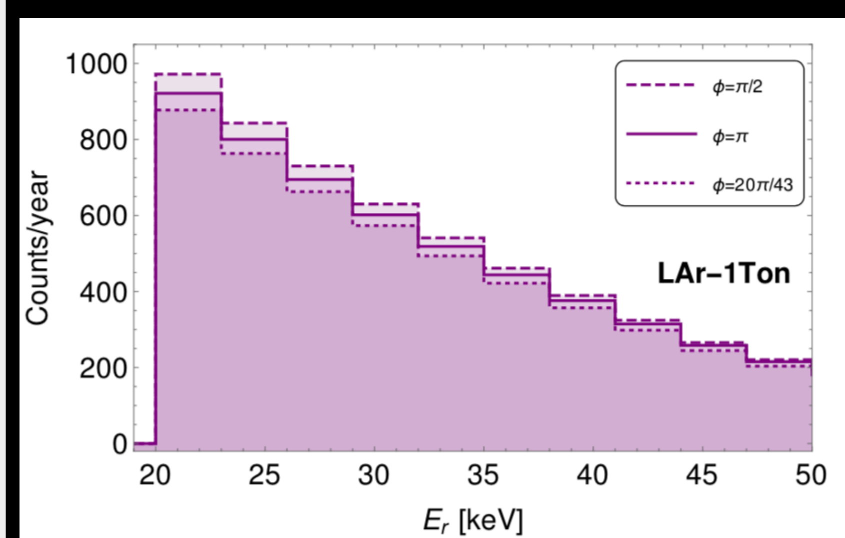
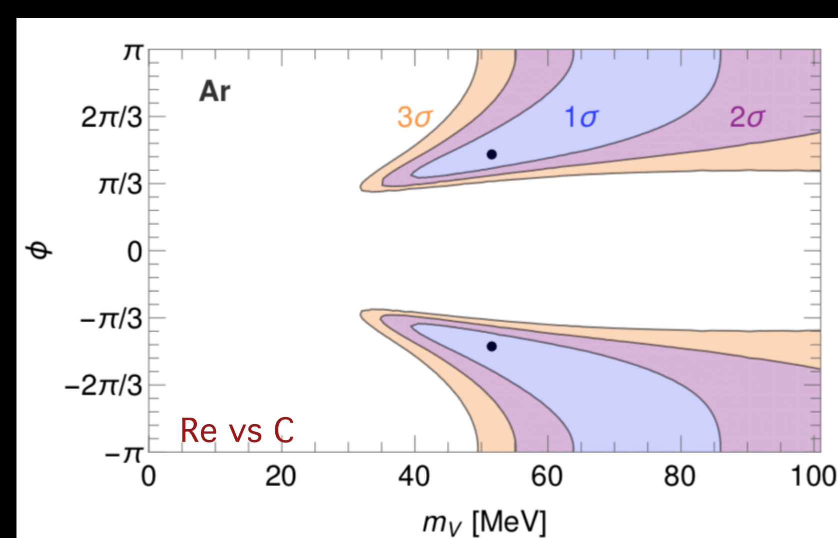
Regions in parameter space exist in which CP violating phases can mimic signals that at first sight can be interpreted as either SM-like or entirely generated by real parameters.





Benchmark parameters for Ar Re vs C pseudo-experiment:
16 MeV, 4.45×10^{-8}, ϕ = Pi

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Conclusions

- Effects of CPV interactions in CEvNS can be studied without considering the complete parameter space through suitable parameterisations (H_V, ϕ)
- Observation of dips in the event rate spectrum can allow to put severe bounds on CPV interactions.
- Features in the event rate spectrum can be used to distinguish the CP-conserving and CP-violating cases.
- CPV interactions can mimic SM-like spectra or spectra generated with CP-conserving interactions $\Rightarrow$ CPV induces degeneracies
- These effects are independent of the experimental source. They apply for CEvNS in ton-size DM detectors or induced by reactor neutrinos.
- CPV effects should be taken into account in the interpretations of CEvNS data!


Thank you!
Standard Model

Backup

CP VIOLATING INTERACTIONS

$$\mathcal{L} = f_V \bar{\nu}\gamma_\mu \nu V^\mu + i f_A \bar{\nu}\gamma_\mu\gamma_5 \nu V^\mu + \sum_{q=u,d} h_V^q \bar{q}\gamma_\mu q V^\mu$$

$$\frac{d\sigma}{dE_r} = \frac{G_F^2 m_i}{2\pi} \left|\xi_V(q_i^2)\right|^2 \left(2 - \frac{E_r m_i}{E_\nu^2} - \frac{2E_r}{E_\nu} + \frac{E_r^2}{E_\nu^2}\right)$$

$$\xi_V(q_i^2) = g_V(q_i^2) - \frac{h_V(q_i^2)(f_V - i f_A)}{\sqrt{2} G_F (q_i^2 - m_V^2)}$$

$$\xi_V = g_V + \frac{|H_V| e^{i\phi}}{\sqrt{2} G_F \left(2 m_i E_r + m_V^2\right)}$$

neutrino vector and axial currents
quark vector interactions
nine parameter problem: the vector boson mass, four moduli and four CP phases (in fV, fA, hVq).

Removing degeneracies

- Unless the spectrum has a rather pronounced feature (a dip) this is somehow expected given that the CEvNS event rate is CP insensitive.

- SM-deg: A signal mimicking the SM prediction in a given detector (nuclide) arises from $|H_V| \ll g_{SM}$, with $|H_V| = 0$ being the extreme case. $|H_V| = 0$ can be due to the vector-quark parameters provided their values assure $\mathrm{Re}(H_V) = \mathrm{Im}(H_V) = 0$, satisfied only if $\phi_{V_u} = \phi_{V_d}$. In that case the fundamental quark-vector couplings are related through

$$h_V^d = -\frac{Z+A}{2A-Z} h_V^u$$

- Re vs C deg: It happens whenever changes of m_V largely compensate for the changes in $|H_V|$ and in the CP-violating phases, thus rendering the signal rather close to the one determined by the pseudo-experiment. It cannot be removed using a multi-target experiment.

- Increasing exposure or decreasing the energy threshold increases sensitivity and therefore leads to better constraints on ϕ.