New physics and Form factors in Coherent Elastic neutrino-nucleus scattering

Jiajun Liao

Sun Yat-sen University

Based on

JL and Marfatia, Phys. Lett. B 775, 54 (2017) [arXiv:1708.04255]

Aristizabal Sierra, JL and Marfatia, 1902.07398

The 14th Workshop on TeV Physics, Nanjing, 04/21/2019

Outline

- Introduction to CEvNS
- COHERENT constraints on NSI
- Impact of form factor uncertainties
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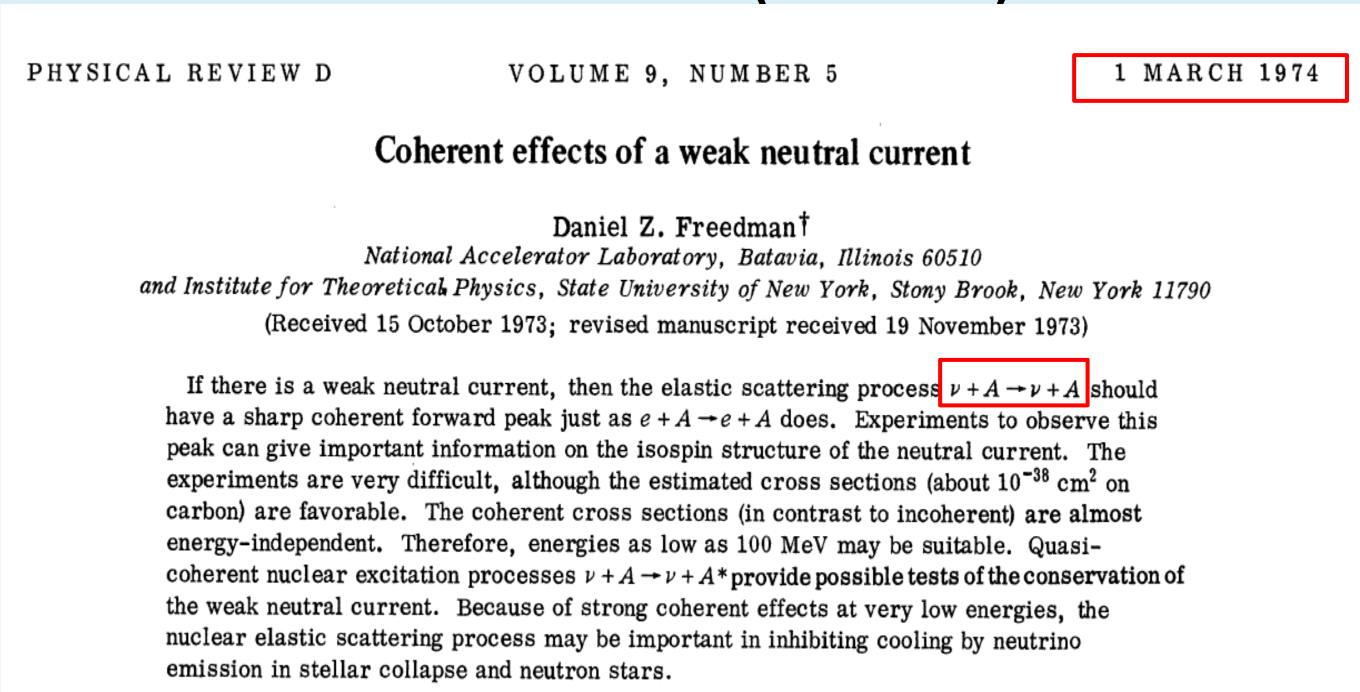
Coherent Elastic neutrino-Nucleus Scattering (CEvNS)



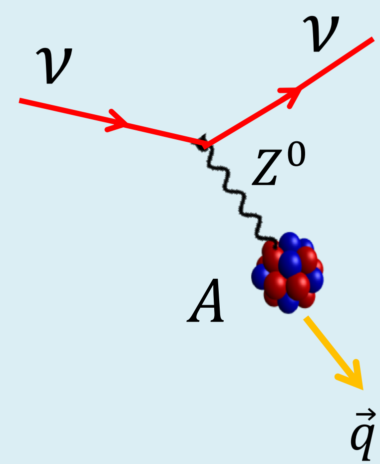
PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \to \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

Daniel Freeman



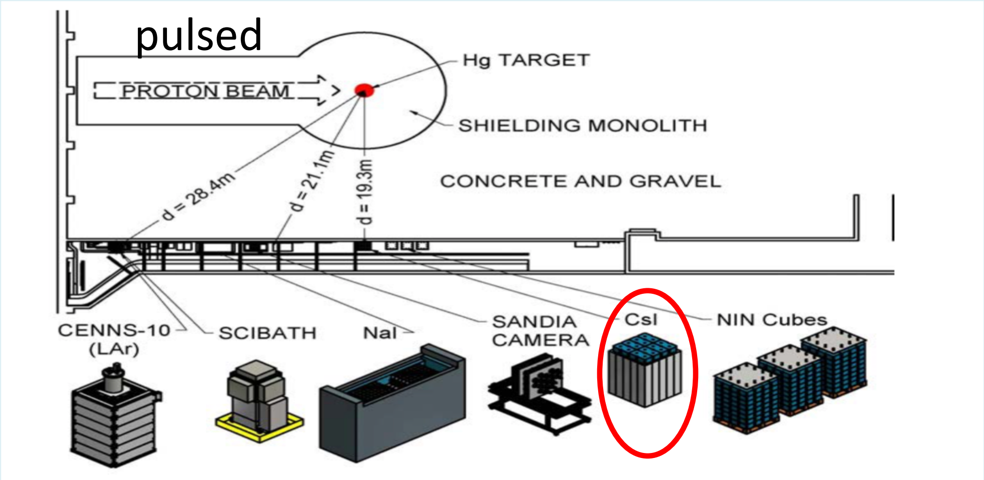
Moment transfer → $Q \lesssim 1/R$ ← Nuclear radius

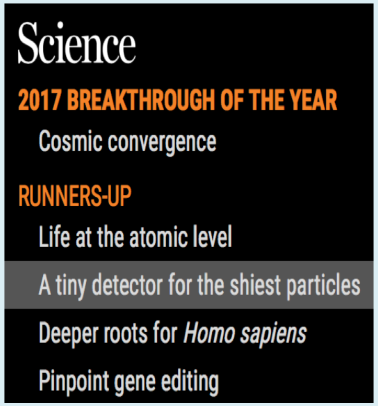
Can be satisfied for $E_\nu < 50 MeV$

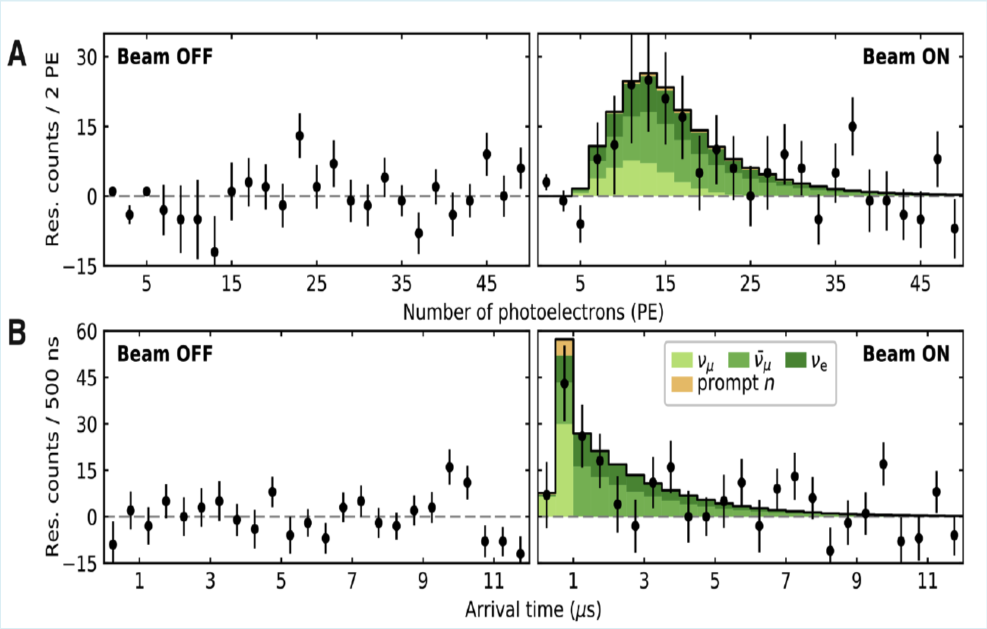
Nuclear recoil energy $E_r \leq \frac{2E_\nu^2}{M+2E_\nu} \sim O(10)$ keV

DM direct detection experiments → detection thresholds of 10 keV

COHERENT experiment







134 ± 22 events observed

173 ± 48 events predicted in SM

6.7σ CL evidence for CEvNS

COHERENT Collaboration, Science 357,1123 (2017)

SM Cross Section

G_F: Fermi Constant

F(q^2): Nuclear form factor

Moment transfer $q^2 = 2ME_r$

$q^2 \to 0, F(q^2) \to 1$ Full Coherence

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

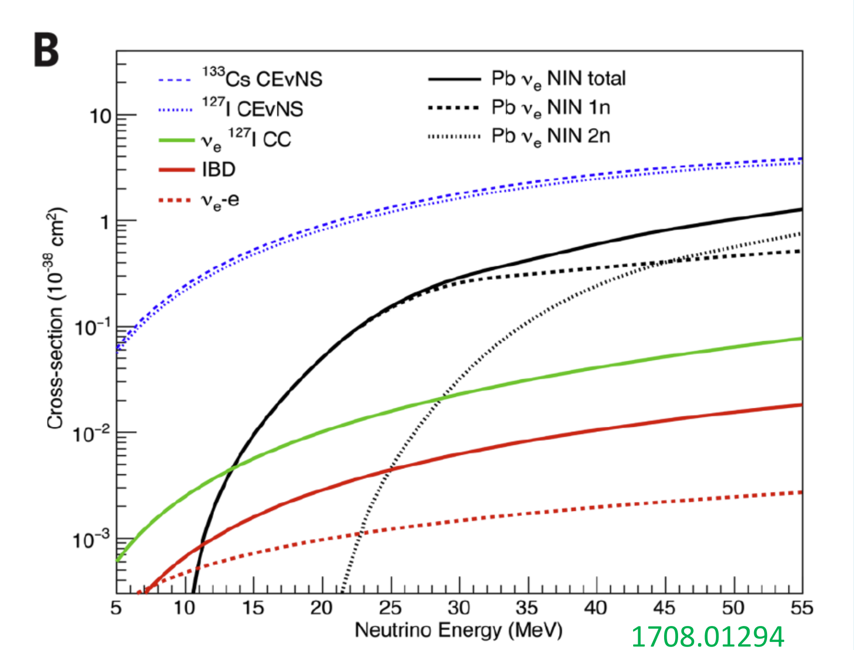
Kinematics from vector interactions

SM nuclear Charge

$$Q_{\rm SM}^2 = \left(Z g_p^V + N g_n^V\right)^2$$

$$g_p^V = \frac{1}{2} - 2\sin^2\theta_W \quad \sim 0.04$$

$$g_n^V = -0.5 \Rightarrow \sigma_{SM} \propto N^2$$



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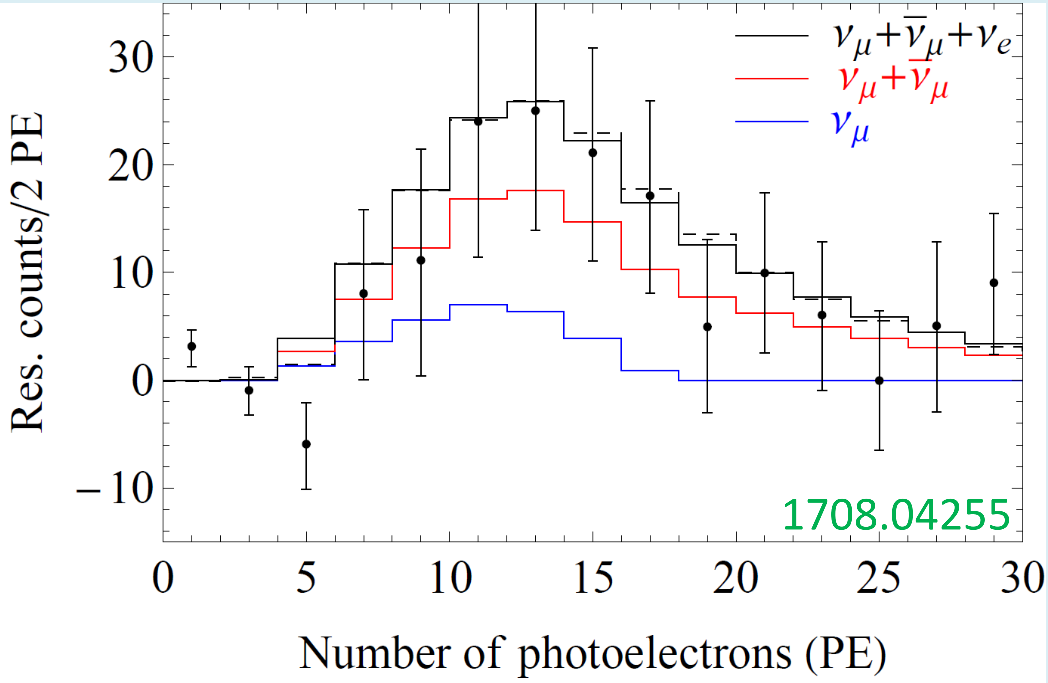
SM spectrum



Neutrinos magnetic moment: Dodd et al. 1991; Scholberg 2005; Kosmas et al. 2015; …

Nonstandard neutrino interactions: Barranco et al. 2005, 2007; Scholberg 2005; …

Neutrino generalized interactions: Lindner et al. 2016; Aristizabal Sierra et al. 2018; …

Sterile neutrinos: Anderson et al. 2012; Dutta et al. 2015; Kosmas et al. 2017; …

Light dark matter: deNiverville et al. 2015; Ge et al. 2018; …

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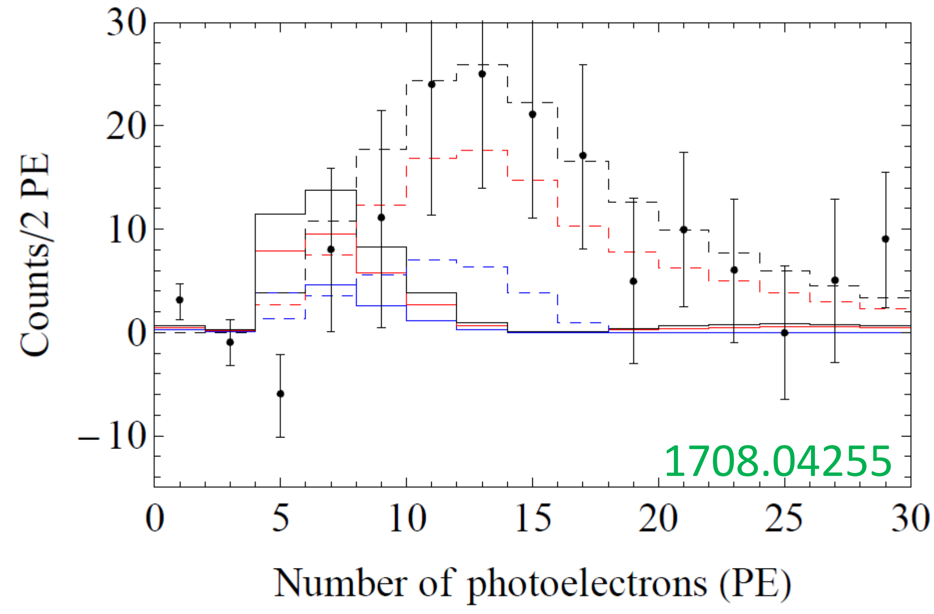
Light vector mediator

$$\mathcal{L}_{\rm NSI} = -g\left(\bar{\nu}\gamma^\rho\nu + \bar{\mu}\gamma^\rho\mu + \bar{u}\gamma^\rho u + \bar{d}\gamma^\rho d\right) Z'_\rho$$

Modified effective nuclear charge

$$Q^2_{\alpha,\rm NSI} = \left[Z\left(g_p^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2+M^2_{Z'})}\right) + N\left(g_n^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2+M^2_{Z'})}\right)\right]^2$$



$M_{Z'} = 10$ MeV and $g = 10^{-4}$

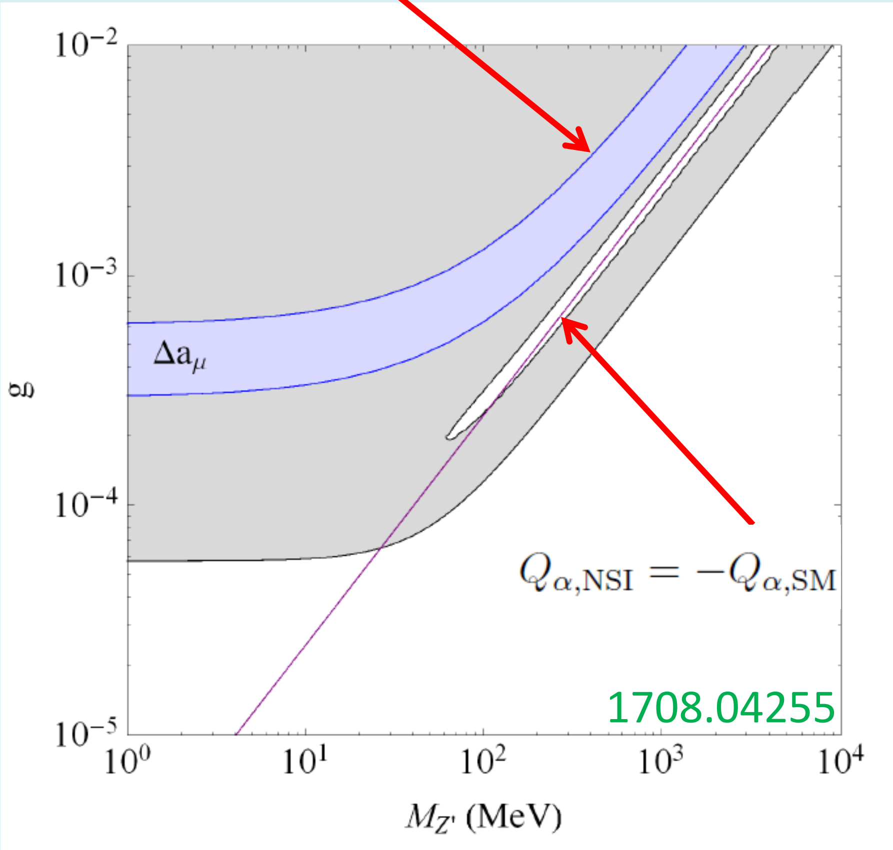
$$\epsilon_{eff} \propto \frac{g^2}{2ME_r + M_{Z'}^2}$$

- NSI matter effect due to forward scattering depends on $\frac{g^2}{M_{Z'}^2}$, For heavy mediators, data sensitive to $\frac{g^2}{M_{Z'}^2}$ and constrain NSI.

- For light mediators, sensitivity to g only, so constraint does not apply to matter NSI arising from light mediator

- Spectral information breaks degeneracy for light mediator

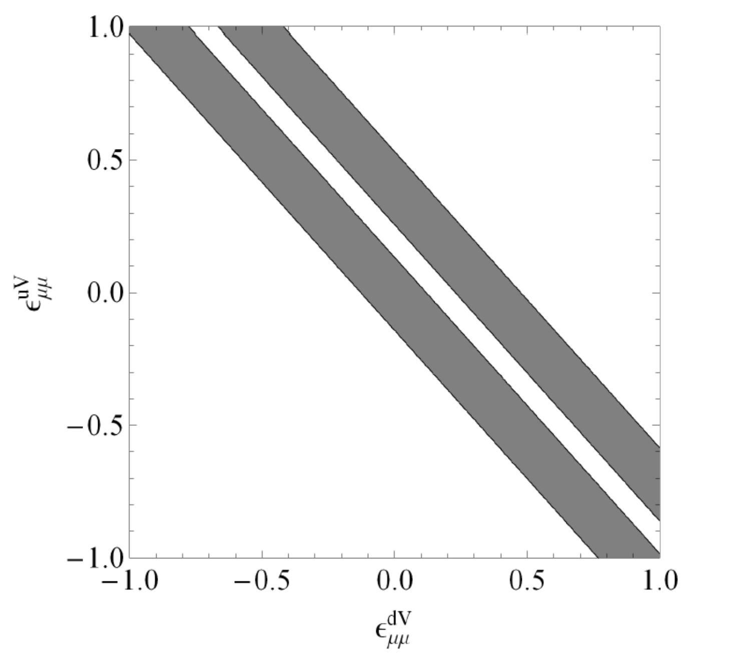
Explains Δa_μ at 2σ

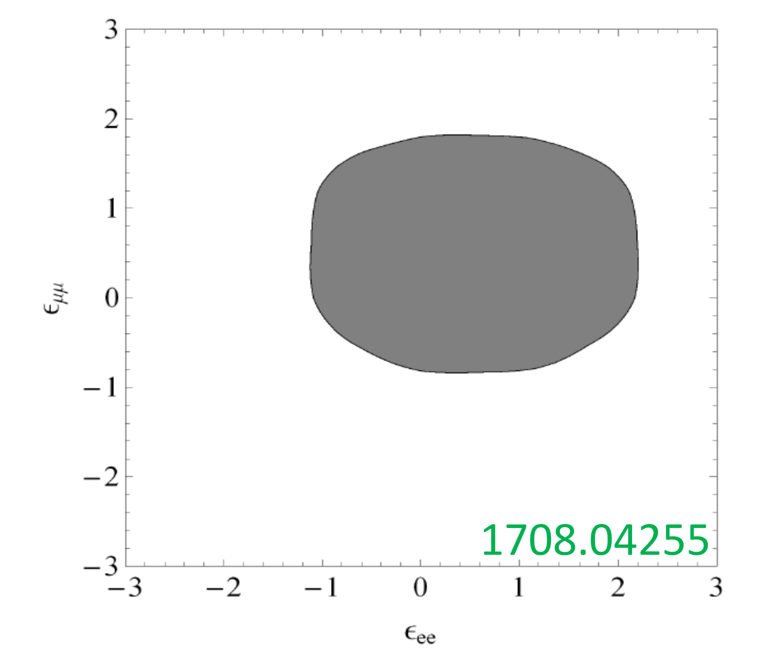


Contact interactions

$$\mathcal{L}_{\text{NSI}} = -\sqrt{2}G_F\epsilon_{\alpha\beta}^{fV}\left[\overline{\nu}_{\alpha L}\gamma^\rho\nu_{\beta L}\right]\left[\bar{f}\gamma_\rho f\right]$$

$$Q_\alpha^2 = \left[Z(g_p^V + 2\epsilon_{\alpha\alpha}^{uV} + \epsilon_{\alpha\alpha}^{dV}) + N(g_n^V + \epsilon_{\alpha\alpha}^{uV} + 2\epsilon_{\alpha\alpha}^{dV})\right]^2 + \sum_{\beta\neq\alpha}\left[Z(2\epsilon_{\alpha\beta}^{uV} + \epsilon_{\alpha\beta}^{dV}) + N(\epsilon_{\alpha\beta}^{uV} + 2\epsilon_{\alpha\beta}^{dV})\right]^2 .$$





$$Zg_p^V + Ng_n^V = \pm\left[Z(g_p^V + 2\epsilon_{\alpha\alpha}^{uV} + \epsilon_{\alpha\alpha}^{dV}) + N(g_n^V + \epsilon_{\alpha\alpha}^{uV} + 2\epsilon_{\alpha\alpha}^{dV})\right]$$

➡ Two Linear bands

Effective parameters

$$\epsilon_{\alpha\alpha} \approx 3(\epsilon_{\alpha\alpha}^{uV} + \epsilon_{\alpha\alpha}^{dV})$$

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Form factor parametrization

$$F(q^2) = \int e^{i\vec{q}\cdot\vec{r}} \rho(r)\, d^3\vec{r} \,.$$

- Helm

$$F_{\mathrm{H}}(q^2) = 3\frac{j_1(qR_0)}{qR_0} e^{-q^2 s^2/2} \,, \qquad \langle r^2\rangle_{\mathrm{H}} = \frac{3}{5}R_0^2 + 3s^2$$

- Symmetrized Fermi distribution

$$F_{\mathrm{SF}}(q^2) = \frac{3}{qc}\left[\frac{\sin(qc)}{(qc)^2}\left(\frac{\pi qa}{\tanh(\pi qa)}\right) - \frac{\cos(qc)}{qc}\right]\left(\frac{\pi qa}{\sinh(\pi qa)}\right)\frac{1}{1+(\pi a/c)^2}$$

$$\langle r^2\rangle_{\mathrm{SF}} = \frac{3}{5}c^2 + \frac{7}{5}(\pi a)^2$$

- Klein-Nystrand

$$F_{\mathrm{KN}}(q^2) = 3\frac{j_1(qR_A)}{qR_A}\frac{1}{1+q^2a_k^2} \,. \qquad \langle r^2\rangle_{\mathrm{KN}} = \frac{3}{5}R_A^2 + 6a_k^2$$

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

$$\frac{d\sigma}{dE_r} = \frac{G_F^2 m_N}{2\pi} \left[N g_V^n F_N(q^2) + Z g_V^p F_Z(q^2)\right]^2 \left(2 - \frac{E_r m_N}{E_\nu^2}\right)$$

- Proton rms radius are known from elastic electron-nucleus scattering to one-per-mille for nuclear isotopes up ton Z=96
- Neutron rms radius are poorly known. Neutron skin: $\Delta r_{np} = r_{\rm rms}^n - r_{\rm rms}^p$

$\Delta r_{np}(^{208}\mathrm{Pb}) = 0.33^{+0.16}_{-0.18}$ fm PREX experiment, Phys. Rev. Lett. 108, 112502 (2012)

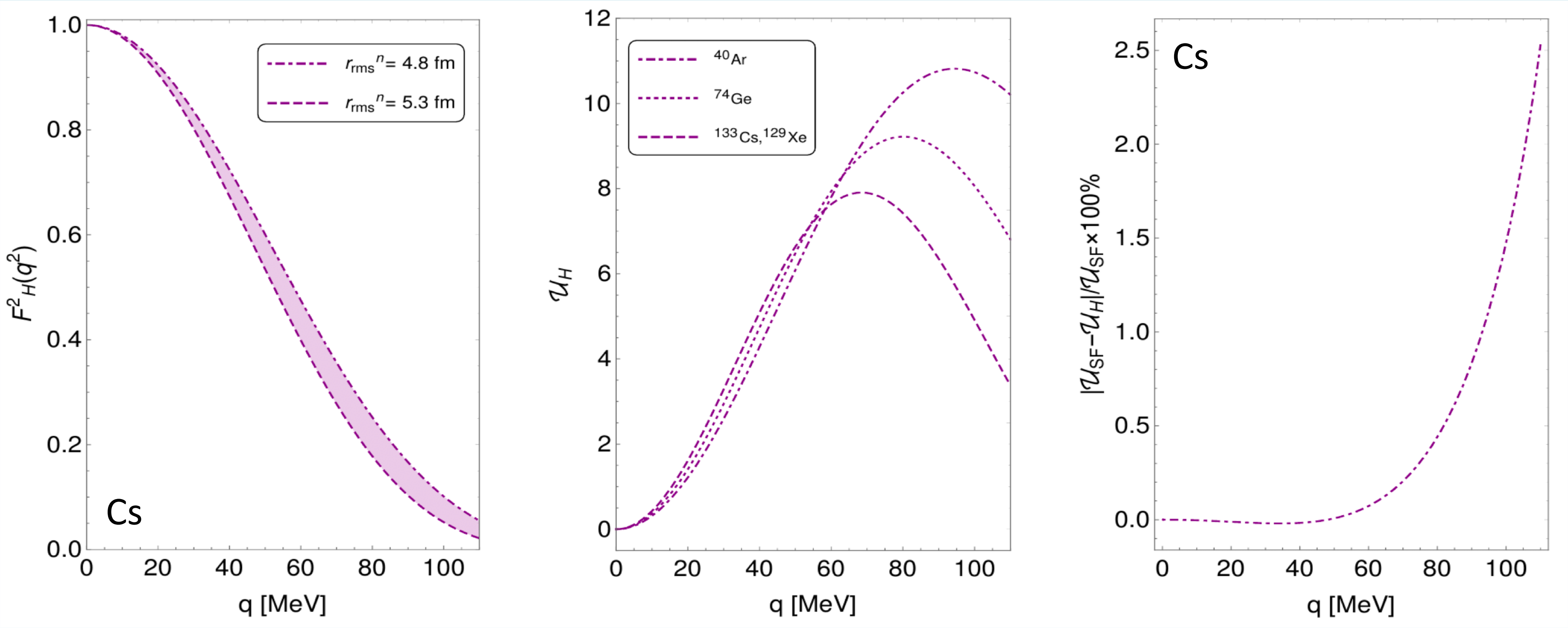
$\Delta r_{np}(\mathrm{CsI}) = 0.7^{+0.9}_{-1.1}$ fm Using COHERENT data, Cadeddu, Giunti, Li, Zhang, Phys. Rev. Lett. 108, 112502 (2012)

(See also $\Delta r_{np}(\mathrm{CsI}) = 0.24^{+2.30}_{-2.03}$ fm Huang and Chen, Arxiv: 1902.07625)

- For protons, fix surface parameter and determine the other by fixing proton rms radius to experimental value
- For neutrons, do the same except allow neutron rms radius to vary within

$$r_{\rm rms}^n|_{\rm min} \equiv r_{\rm rms}^p\,, \quad r_{\rm rms}^n|_{\rm max} \equiv r_{\rm rms}^p + 0.5~\mathrm{fm}$$

Form factor uncertainties



$$\mathcal{U}_H = \left| F_H^2(q^2)|_{r^n_{\rm rms}=r^p_{\rm rms}} - F_H^2(q^2)|_{r^n_{\rm rms}=r^p_{\rm rms}+0.5\,{\rm fm}} \right| \times 100\%$$

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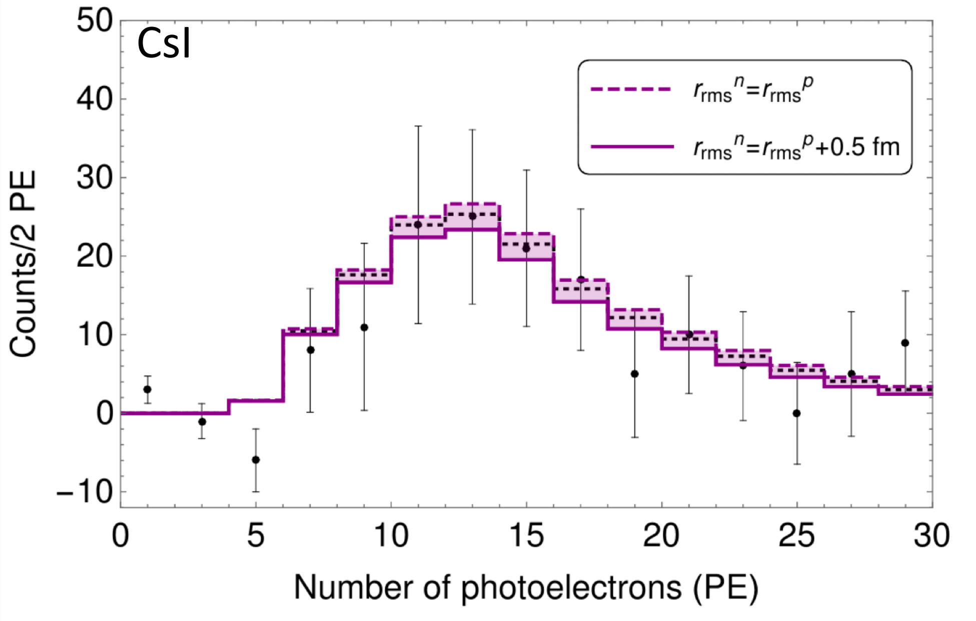
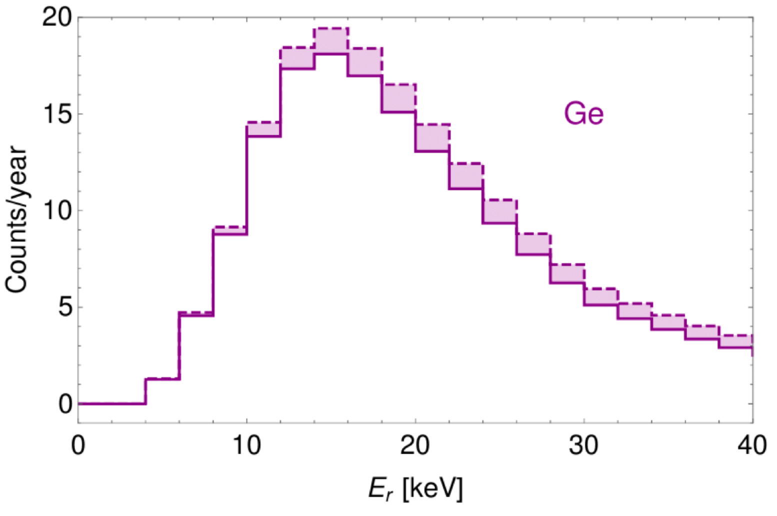
- FF uncertainties are relevant for $q \gtrsim 20$ MeV
- Percentage uncertainties reach maximum at $q \approx 65$ MeV
- Size of the uncertainties do not depend on the FF parameterization chosen

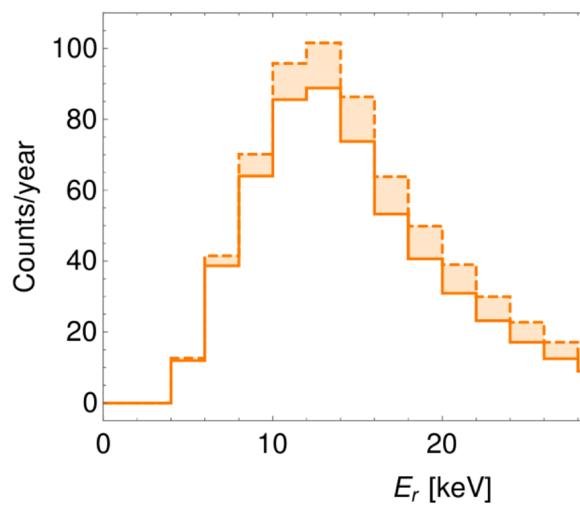
COHERENT phase I



COHERENT phase II



COHERENT phase III



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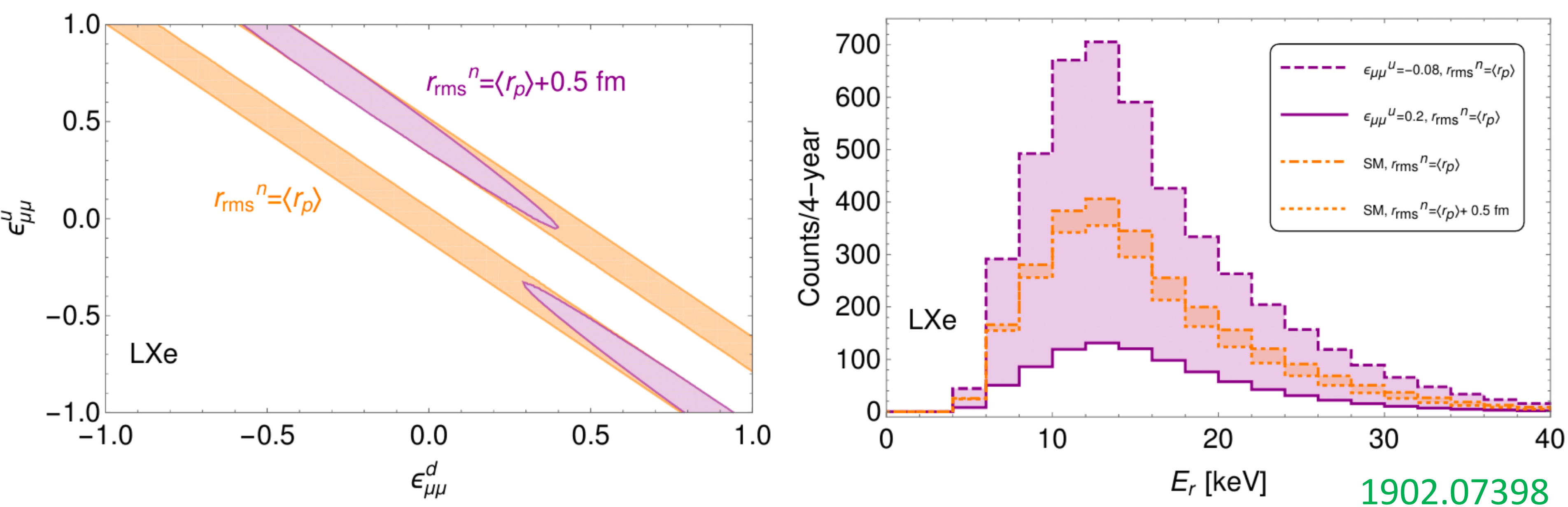
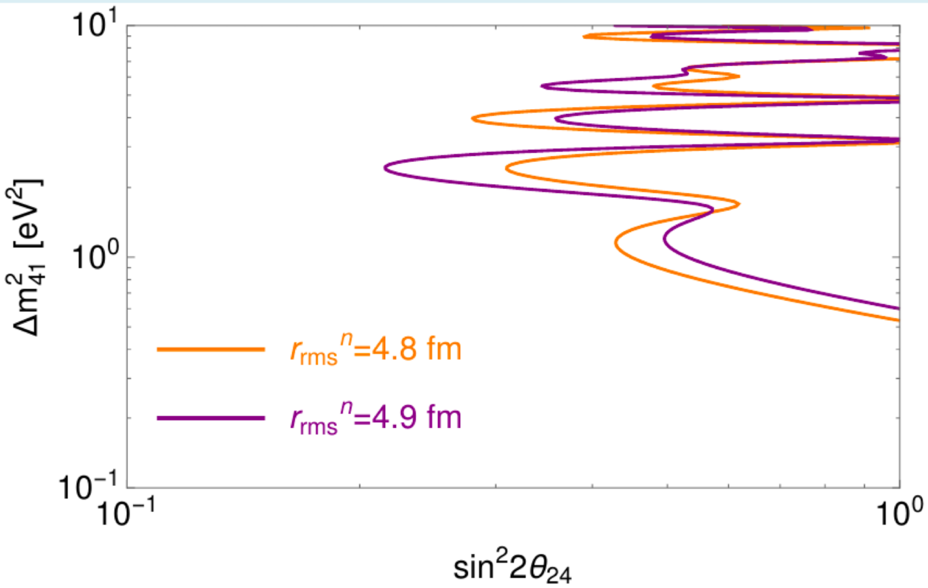
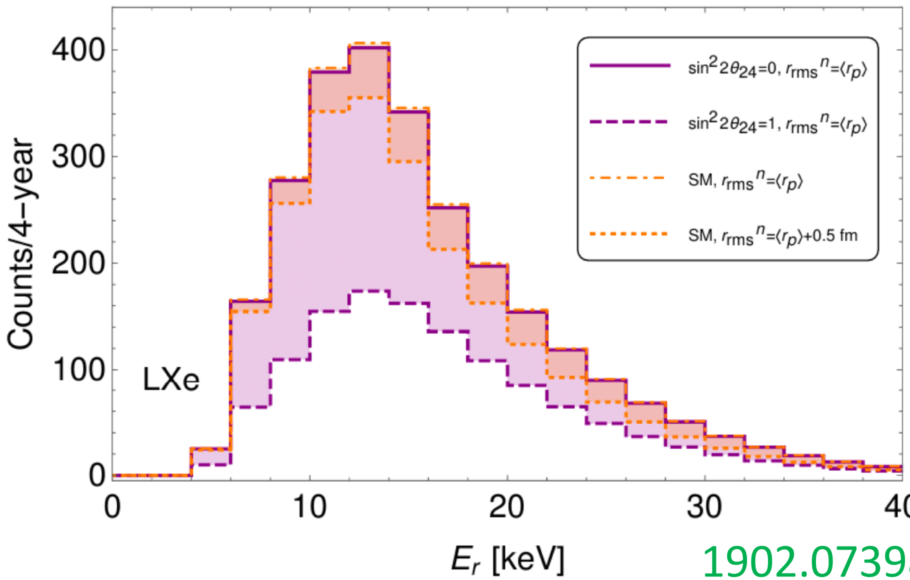
Neutrino Nonstandard Interactions



- Various ranges of NSI couplings that will produce signals that cannot be disentangled from the SM signal.

Sterile Neutrinos





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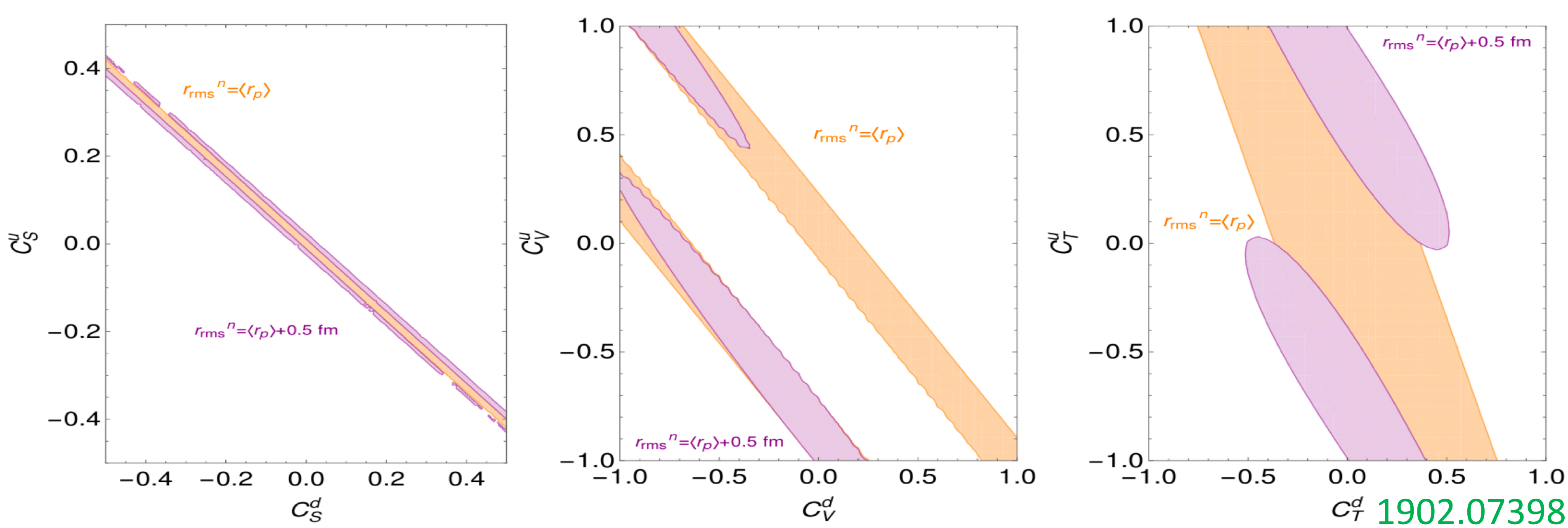
- A 2% change in neutron radius has a big effect on the sterile neutrino parameter exclusion

Neutrino Generalized Interactions

$$\mathcal{L}_{\rm NGI} = \frac{G_F}{\sqrt{2}} \sum_{\substack{a=S,P,V,A,T\\ q=u,d}} [\bar{\nu}\Gamma^a \nu]\ [\bar{q}\Gamma_a (C_a^q + i\gamma_5 D_a^q) q]$$

$$\Gamma_a = \{\mathbb{I}, i\gamma_5, \gamma_\mu, \gamma_\mu\gamma_5, \sigma_{\mu\nu}\}$$



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- Depending on the value of neutron rms radius large portions of parameter space are allowed or disfavored.

Summary

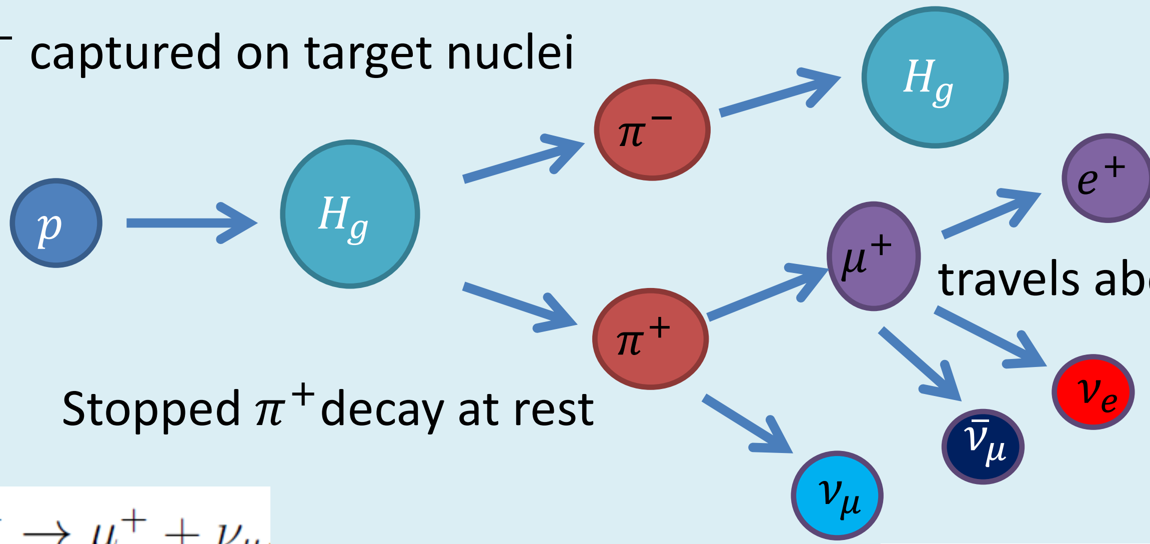
- For light mediators, COHERENT data only constrain the mediator coupling, and COHERENT bounds on matter NSI parameters obtained using contact approx don't apply for $M_{Z'} < 50$ MeV.
- For heavy mediators, the COHERENT data can place meaningful constraints on the effective NSI parameters in Earth matter.
- FF uncertainties are independent of the parameterization chosen, and relevant for $q \gtrsim 20$ MeV , so not important for CEvNS induced by reactor and solar neutrinos.
- New physics searches are strongly impacted by FF uncertainties.

Thank you!

Backup slides

SNS Neutrino Flux

π^- captured on target nuclei



Stopped π^+ decay at rest

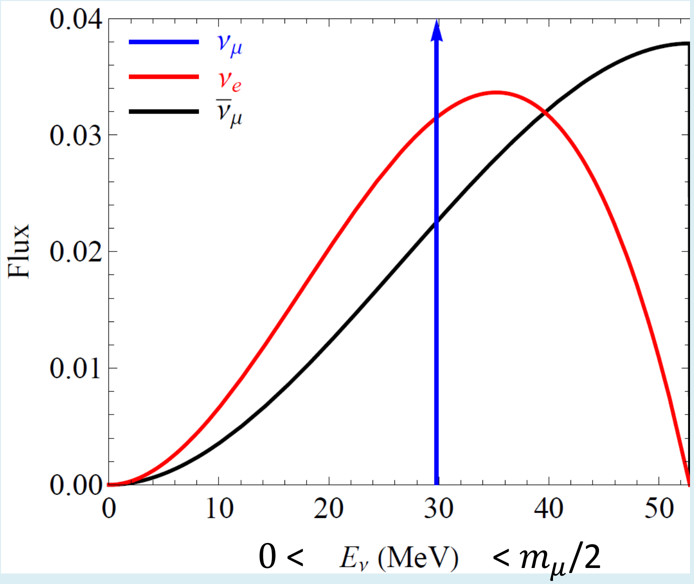
$$\pi^+ \to \mu^+ + \nu_\mu$$

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

$$\phi_{\nu_\mu}(E_\nu) = \delta\left(E_\nu - \frac{m_\pi^2 - m_\mu^2}{2m_\pi}\right),$$

$$\phi_{\bar{\nu}_\mu}(E_\nu) = \frac{64E_\nu^2}{m_\mu^3}\left(\frac{3}{4} - \frac{E_\nu}{m_\mu}\right),$$

$$\phi_{\nu_e}(E_\nu) = \frac{192E_\nu^2}{m_\mu^3}\left(\frac{1}{2} - \frac{E_\nu}{m_\mu}\right),$$



$$N_\alpha^i = \frac{r N_{\mathrm{POT}}}{4\pi L^2} \times \frac{2 m_{\mathrm{det}}}{M_{\mathrm{CsI}}} N_A \times \int dn_{\mathrm{PE}} f(n_{\mathrm{PE}}) \frac{dE_r}{dn_{\mathrm{PE}}} \int dE_\nu \phi_\alpha(E_\nu) \frac{d\sigma_\alpha}{dE_r}(E_\nu, E_r)$$

$r = 0.08$ is the number of neutrinos per favor for each proton on target

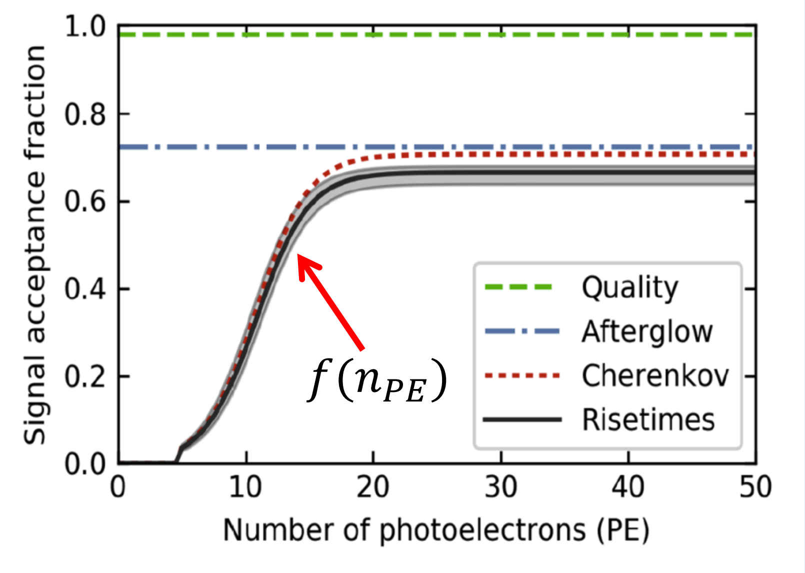
$N_{POT} = 1.76\times10^{23}$ is the total number of protons delivered to the target

$L = 19.3$ m is the distance between the source and the CsI detector

$m_{det} = 14.6$ kg is the mass of detector, M_{CsI} is the molar mass of CsI

"Approximately 1.17 photoelectrons are expected per keV of cesium or iodine nuclear recoil energy"

$$n_{\mathrm{PE}} = 1.17 \left(\frac{E_r}{\mathrm{keV}} \right)$$



COHERENT Collaboration, Science (2017)

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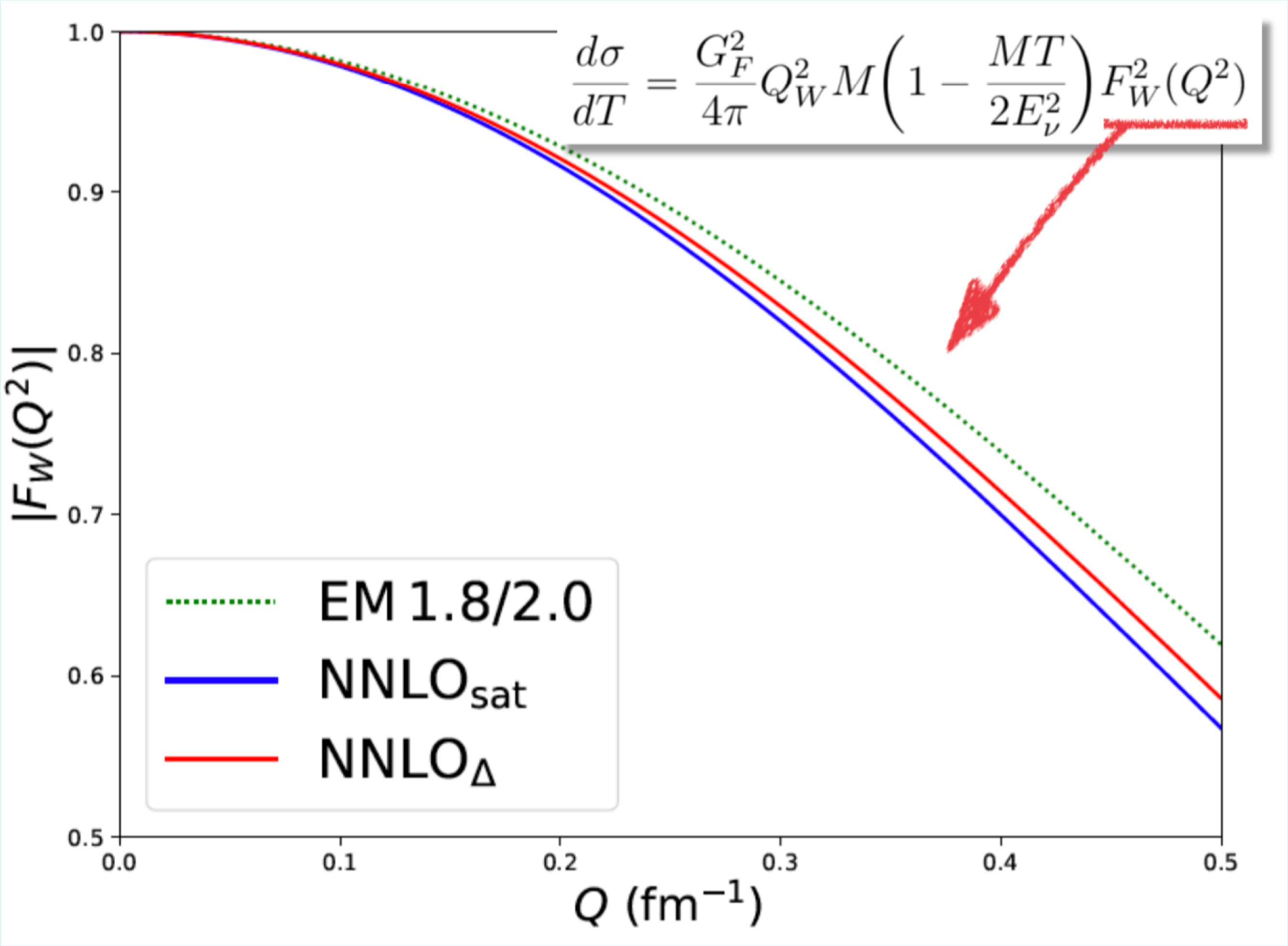

From Gaute Hagen