Search for *New Physics* with Coherent elastic neutrino-nucleus scattering

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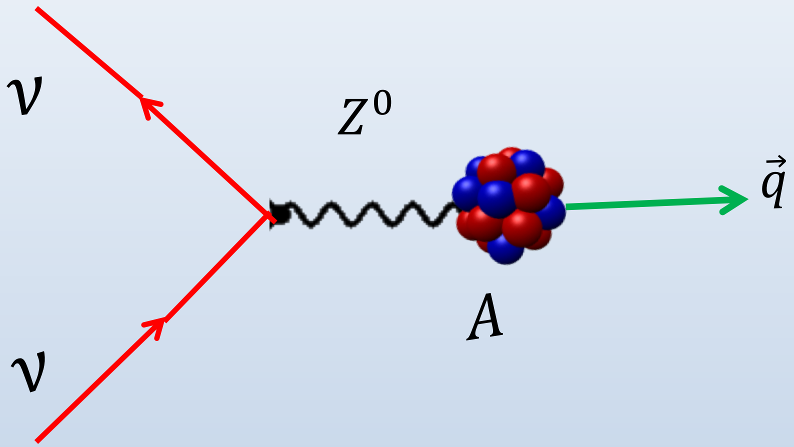
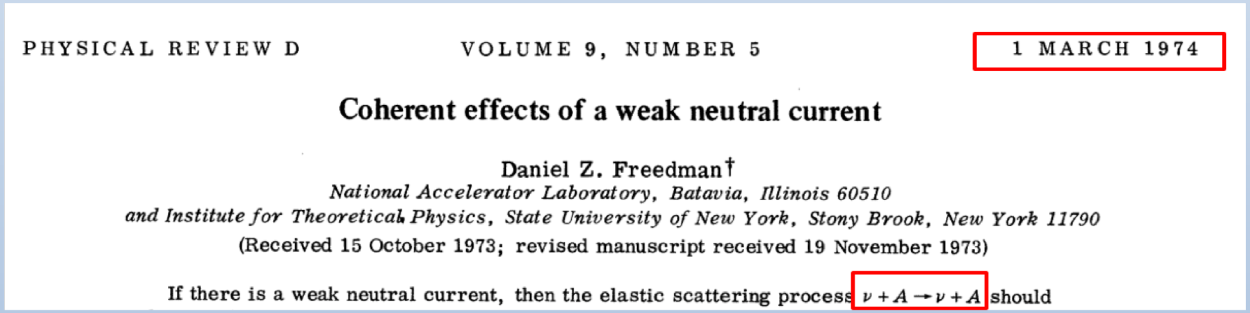
FLASY2019, USTC, Hefei, 7/24/2019

Outline

- Introduction to CEvNS
- COHERENT constraints on NSI
- Impact of Form Factor uncertainties
- Summary

Coherent Elastic ν-Nucleus Scattering





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)

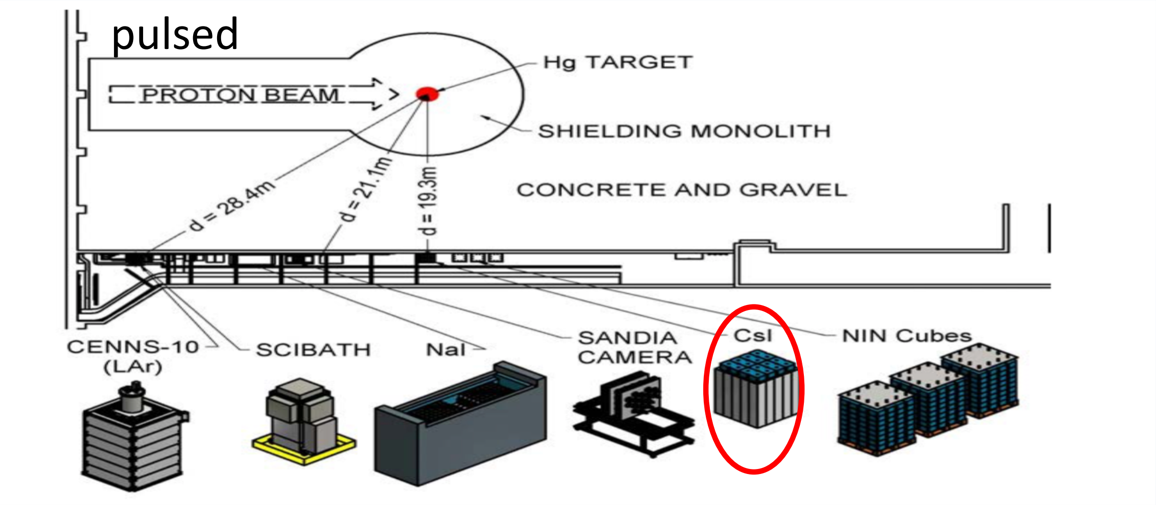
If there is a weak neutral current, then the elastic scattering process $\boxed{\nu + A \to \nu + A}$ should

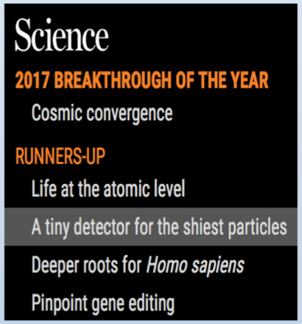
Moment transfer $\longrightarrow$ $q \lesssim 1/R$ $\longleftarrow$ Nuclear radius

Satisfied for $E_\nu < 50\ \mathrm{MeV}$ Nuclear recoil energy $E_r \le \frac{2E_\nu^2}{M+2E_\nu} \sim O(10)$ keV

DM direct detection experiments $\Longrightarrow$ detection thresholds of 10 keV

COHERENT




Science

2017 BREAKTHROUGH OF THE YEAR

Cosmic convergence

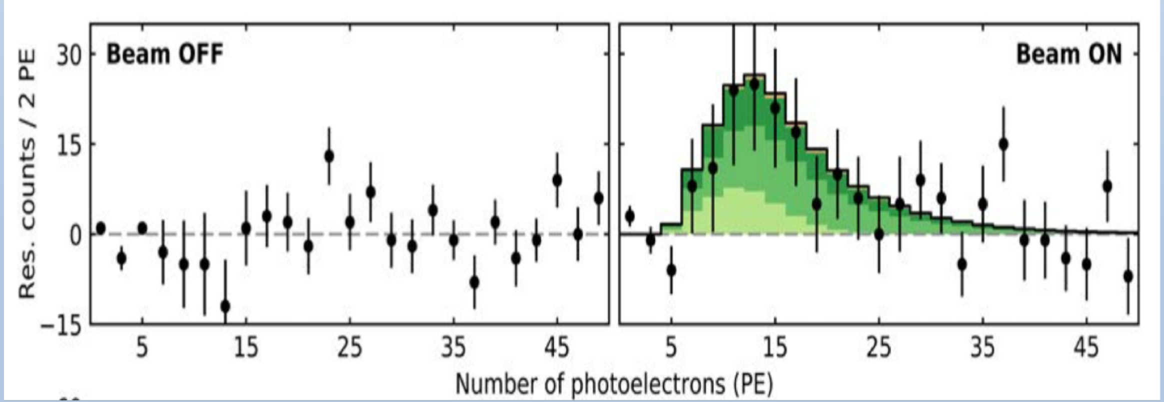
RUNNERS-UP

Life at the atomic level

A tiny detector for the shiest particles

Deeper roots for *Homo sapiens*

Pinpoint gene editing



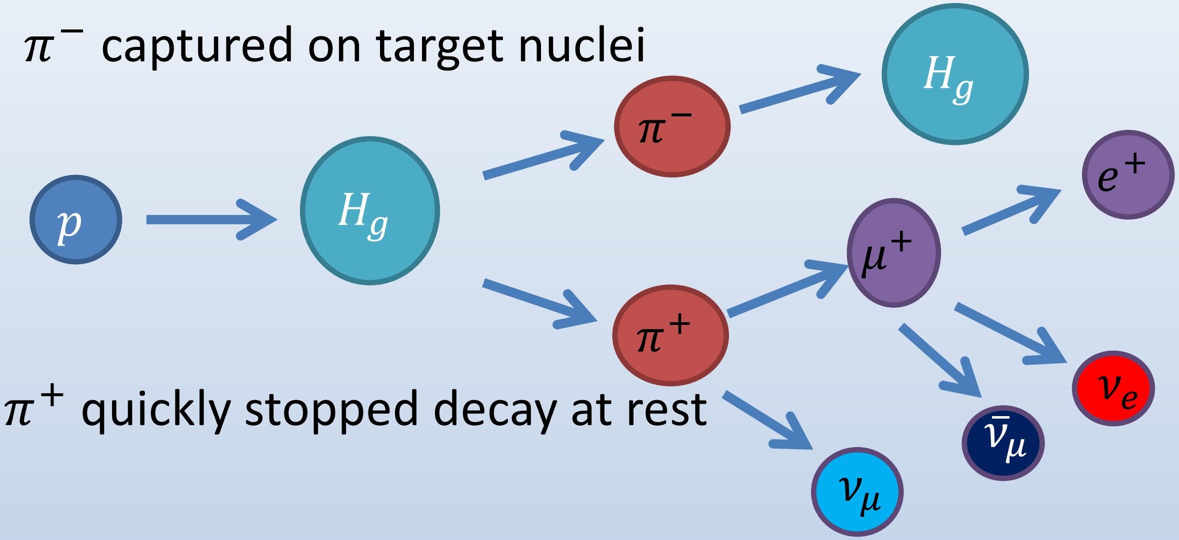
COHERENT Collaboration, Science 357,1123 (2017)

134 ± 22 observed

173 ± 48 predicted in SM

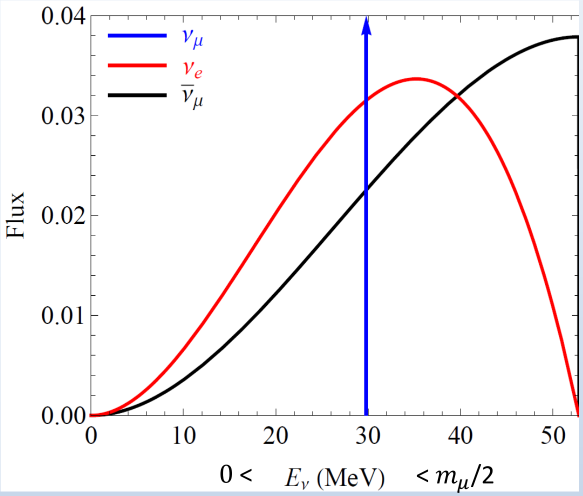
6.7σ CL evidence for CEvNS

Flavor information

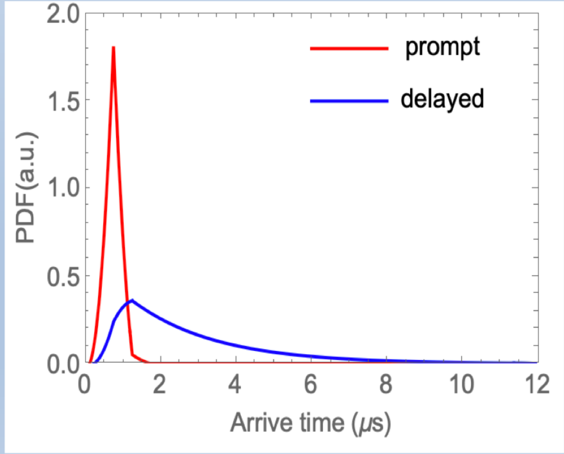


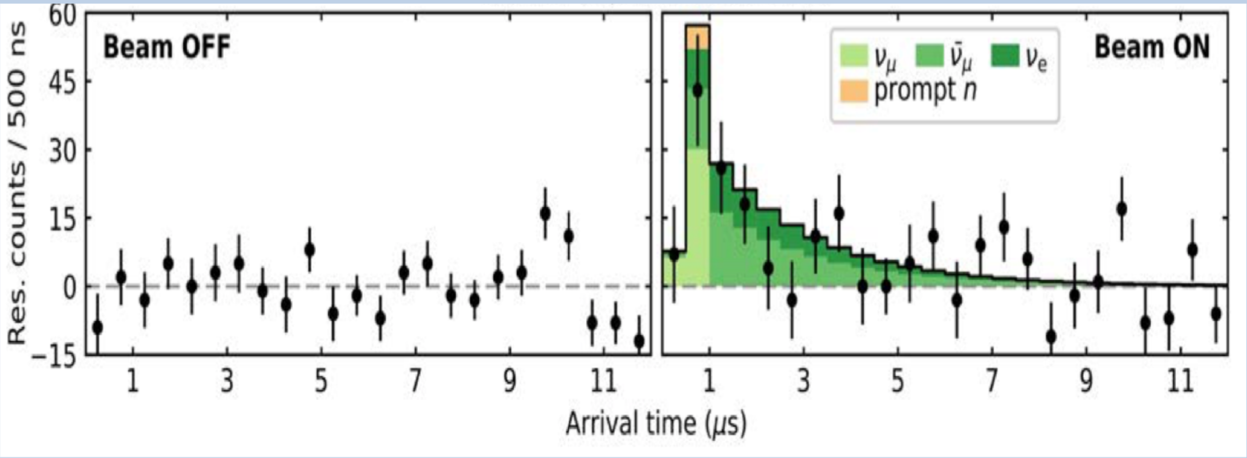
π^- captured on target nuclei

π^+ quickly stopped decay at rest



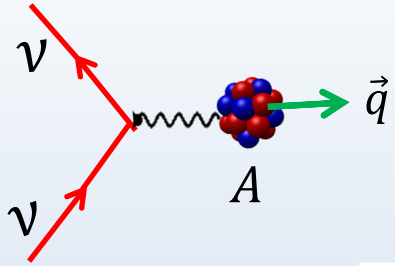
μ^+ travels about 1 cm and stopped, then decay at rest





COHERENT Collaboration, Science 357,1123 (2017)

CEvNS in SM



Elementary Particle Physics   Nuclear Physics

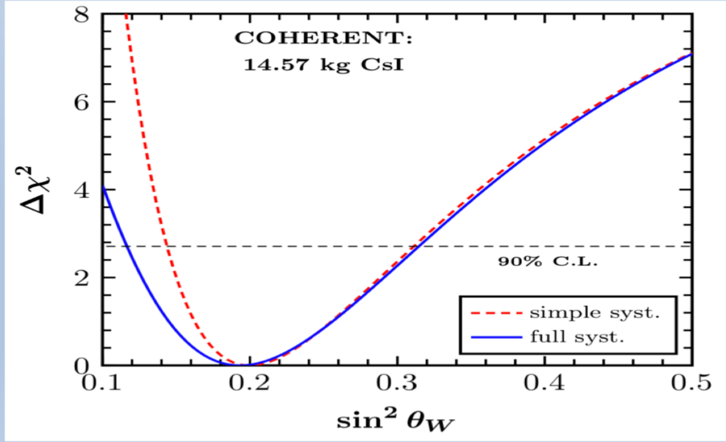
$$\frac{d\sigma}{dE_r} = \frac{G_F^2 m_N}{2\pi} Q_{\mathrm{SM}}^2 \left(2 - \frac{E_r m_N}{E_\nu^2}\right) F(q^2)^2$$

Kinematics from vector interactions

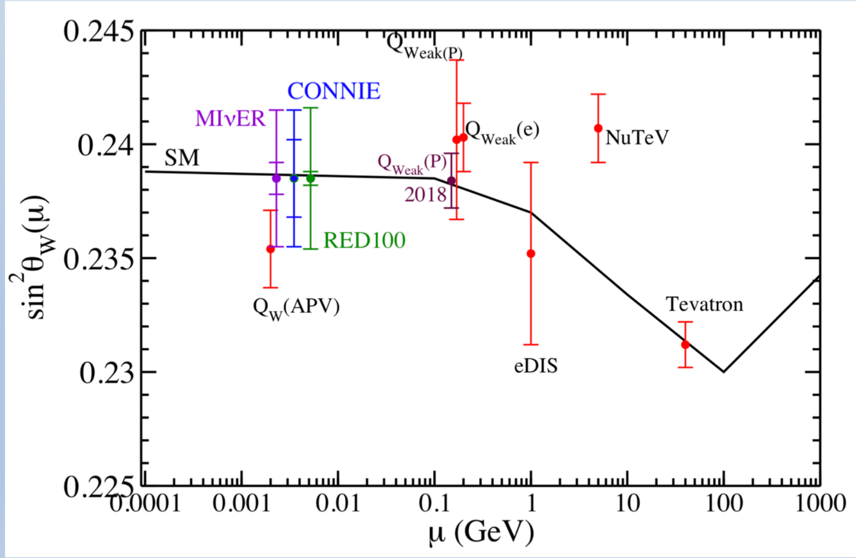
SM weak charge: $Q_{\mathrm{SM}}^2 = \left(Z g_p^V + N g_n^V\right)^2$

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

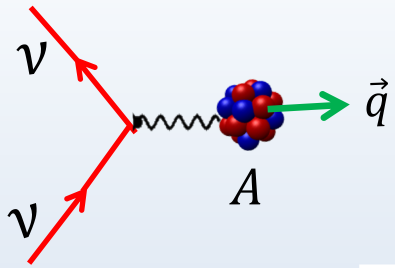
$g_n^V = -0.5$ $\Rightarrow$ $\sigma_{SM} \propto N^2$



Papoulias, Kosmas, Phys. Rev. D97, 033003(2018)



Cañas, Garcés, Miranda, Parada, Phys.Lett. B784, 159 (2018)

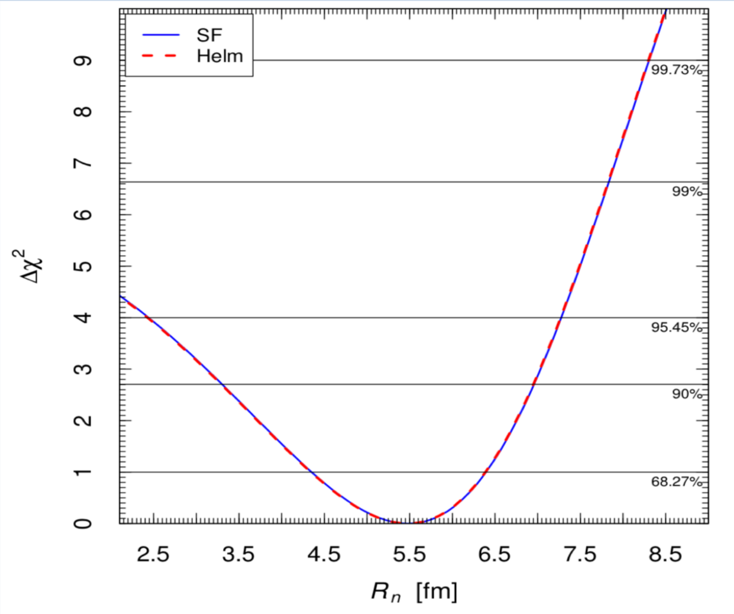


CEvNS in SM

Elementary Particle Physics Nuclear Physics

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

First average CsI neutron radius measurement



Cadeddu, Giunti, Li, Zhang, Phys. Rev. Lett. 120, 072501 (2018)

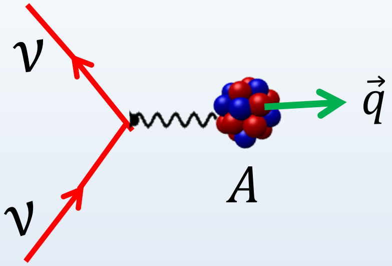
F(q^2): Nuclear form factor

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

$$F_{\rm Helm}(q^2) = 3\frac{j_1(qR_0)}{qR_0} e^{-q^2 s^2/2}$$

R. H. Helm, Phys. Rev. 104, 1466 (1956)

$$R_n^2 = \frac{3}{5} R_0^2 + 3s^2$$



New Physics

- NSI: Barranco et al. 0508299; Scholberg 0511042; Dutta et al. 1508.07981; Lindner et al. 1612.04150; Dent et al. 1612.06350; Coloma et al. 1708.02899; Liao et al. 1708.04255; Dent et al. 1711.03521; Papoulias et al. 1711.09773; Farzan et al. 1802.05171; Abdullah et al. 1803.01224; Bauer et al. 1803.05466; Denton et al. 1804.03660; Billard et al. 1805.01798; Altmannshofer et al. 1812.02778; Aristizabal Sierra et al. 1902.07398; Miranda et al. 1902.09036; Dutta et al. 1903.10666; Aristizabal Sierra et al. 1906.01156…
- NGI: Lindner et al. 1612.04150; Papoulias et al. 1711.09773; Aristizabal Sierra et al. 1806.07424, 1902.07398; Altmannshofer et al. 1812.02778; Bischer et al. 1905.08699;
- Sterile neutrinos: Anderson et al. 1201.3805; Dutta et al. 1511.02834; Papoulias et al. 1711.09773; Aristizabal Sierra et al. 1902.07398; Miranda et al. 1902.09036;
- Neutrino magnetic moment: Dodd et al. 1991; Scholberg 0511042; Kosmas et al. 1505.03202; Papoulias et al. 1711.09773; Billard et al. 1805.01798; Miranda et al. 1905.03750;
- DM: deNiverville et al. 1505.07805; Ge et al. 1710.10889; Brdar et al. 1810.03626; Dutta et al. 1906.10745;

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Matter NSI

Wolfenstein, Phys. Rev. D 17, 2369 (1978)

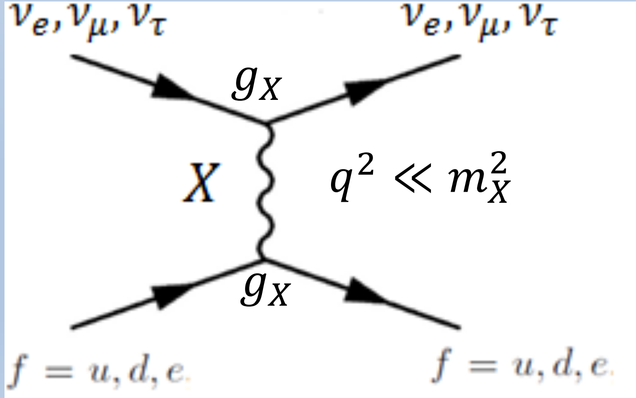
$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F \sum_{\alpha\beta fC} \epsilon^{fC}_{\alpha\beta}\left[\bar{\nu}_{\alpha L}\gamma^{\rho}\nu_{\beta L}\right]\left[\bar{f}\gamma_{\rho}P_C f\right]$$

Modification of matter potential

$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^{\dagger} + A\begin{pmatrix}\overset{\text{SM}}{\boxed{1}}+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon^{*}_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon^{*}_{e\tau} & \varepsilon^{*}_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

Coherent forward scattering $q^2 \rightarrow 0$

$$\epsilon_{\alpha\beta} \equiv \sum_f \epsilon^{fV}_{\alpha\beta}\frac{N_f}{N_e}$$



$$\varepsilon \propto \frac{g_X^2 m_W^2}{m_X^2}$$

(i) Heavy mediator, $m_X \sim$ 1 TeV, $g_X \sim 1$, $\varepsilon \sim 0.01$

(ii) Light mediator, $m_X \sim$ 10 MeV, $g_X \sim 10^{-5}$, $\varepsilon \sim 1$

Farzan, Phys. Lett. B748, 311 (2015)

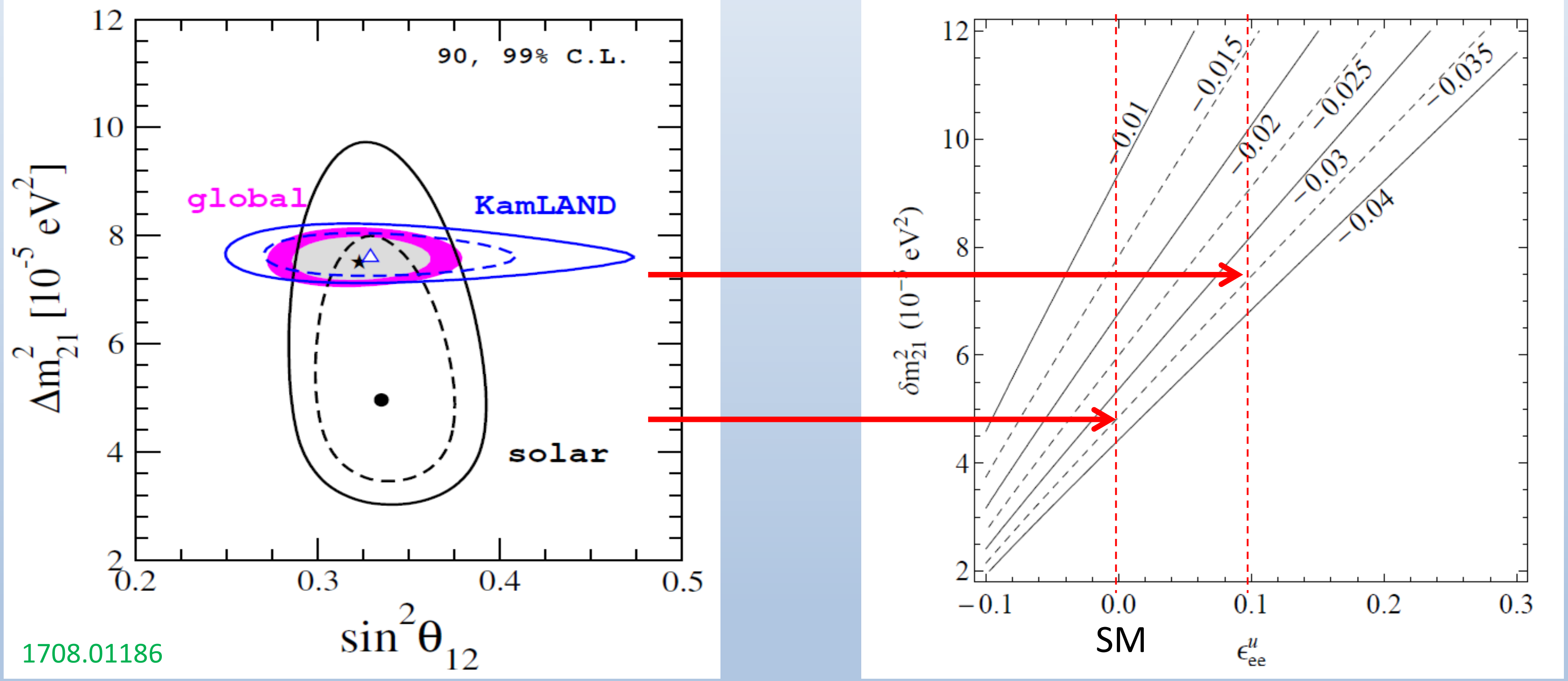
Motivation

SK, 1606.07538

$$A_{\rm DN}^{\rm fit,\,SK} = (-3.3 \pm 1.0(\text{stat.}) \pm 0.5(\text{syst.}))\%$$

JL, Marfatia, Whisnant, Phys. Lett. B 771, 247(2017)

$$\epsilon^{u}_{ee} = \epsilon^{d}_{ee} \sim 0.1$$



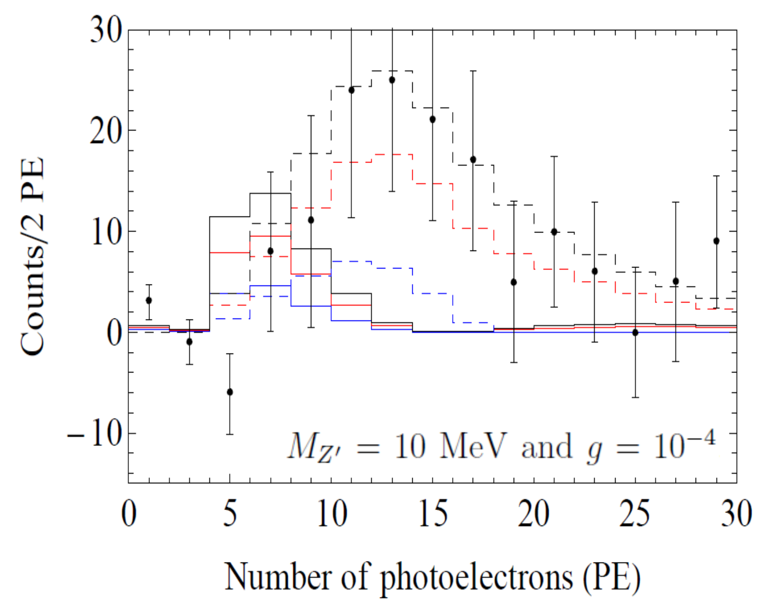
1708.01186

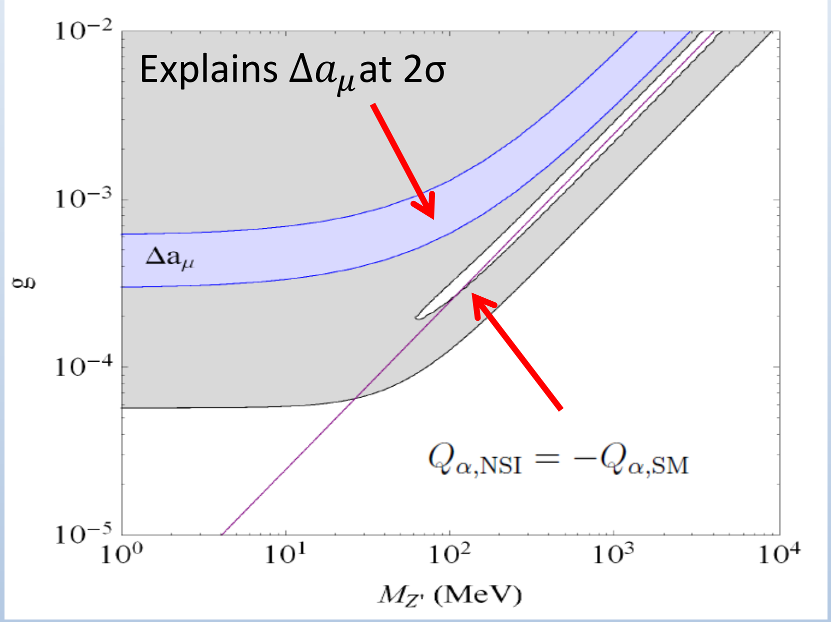
Light Mediator

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

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

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



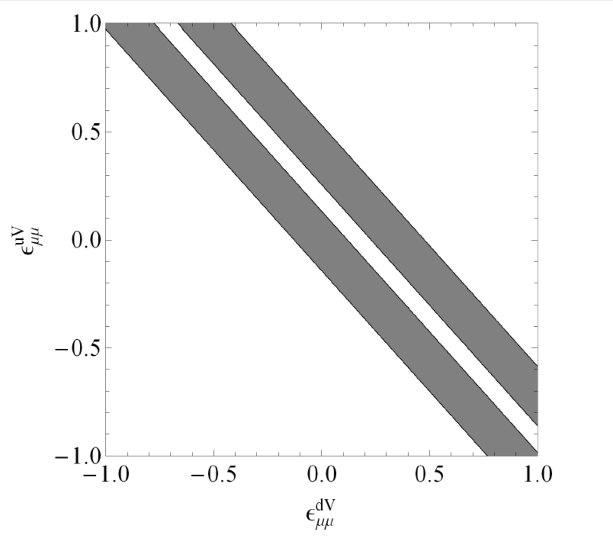


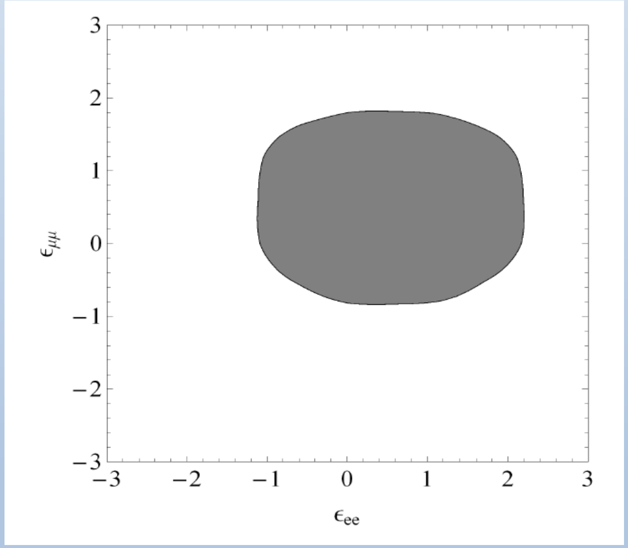
- NSI matter effect depends on $\frac{g^2}{M^2_{Z'}}$ due to coherent forward scattering
- For heavy mediators, data sensitive to $\frac{g^2}{M^2_{Z'}}$ and constrain NSI
- For light mediators, sensitivity to g only, so constraint does not apply

Heavy Mediator

$$\mathscr{L}_{\rm NSI} = -2\sqrt{2}G_F \sum_{f,C,\alpha,\beta} \epsilon_{\alpha\beta}^{fP}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu P_C f)$$
$$= -\sqrt{2}G_F\epsilon_{\alpha\beta}^{fV}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu f) - \sqrt{2}G_F\epsilon_{\alpha\beta}^{fA}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu\gamma^5 f)$$

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





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

⇨ Two Linear bands

Effective parameters measured in neutrino oscillation experiments

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

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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 R. H. Helm, Phys. Rev. 104, 1466 (1956)

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

- Symmetrized Fermi distribution D. W. L. Sprung and J. Martorell, Journal of Physics A: Math-ematical and General 30, 6525 (1997),

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

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

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

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

Form factor uncertainties

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

$$\Downarrow$$

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

- 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: $\Delta r_{np} = r^n_{\rm rms} - r^p_{\rm rms}$

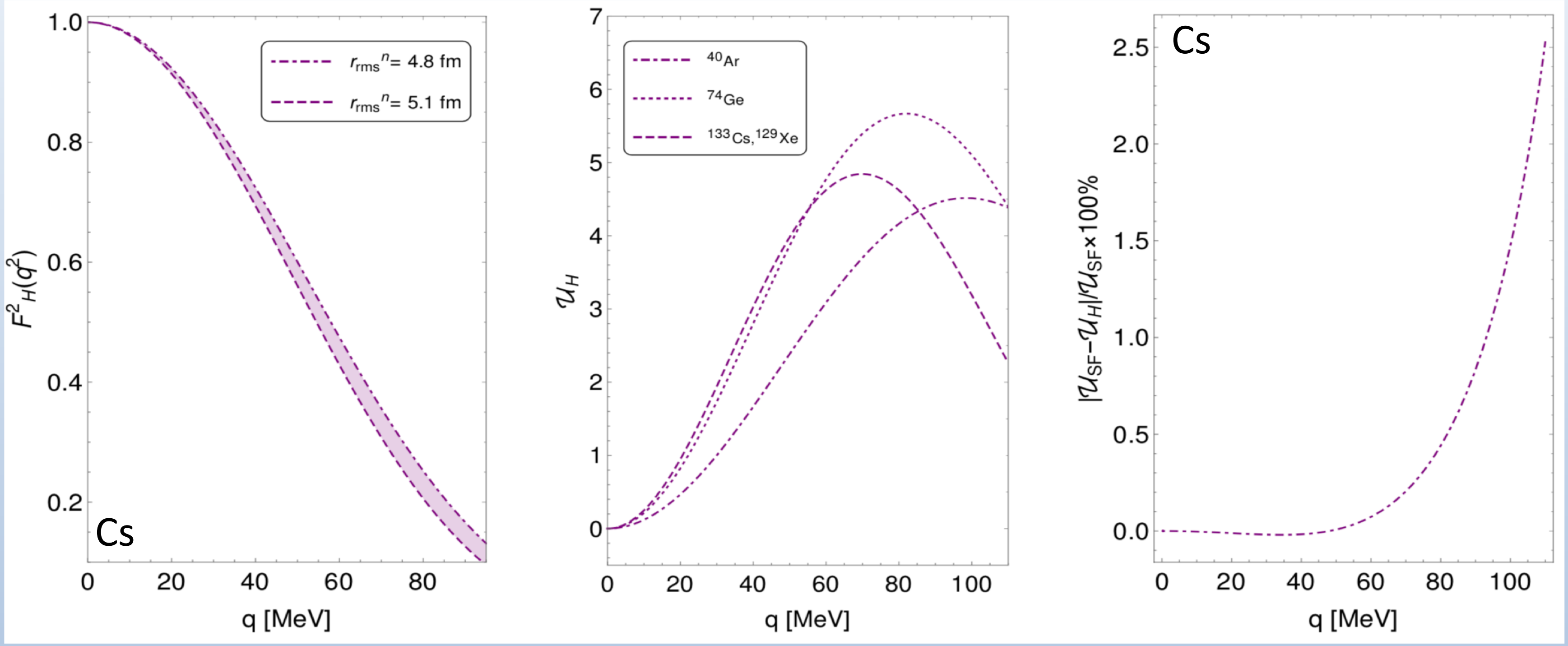
$\Delta r_{np}(^{208}\text{Pb}) = 0.33^{+0.16}_{-0.18}\ \text{fm}$ PREX experiment, Phys. Rev. Lett. 108, 112502 (2012)

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

- 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

Form factor uncertainties

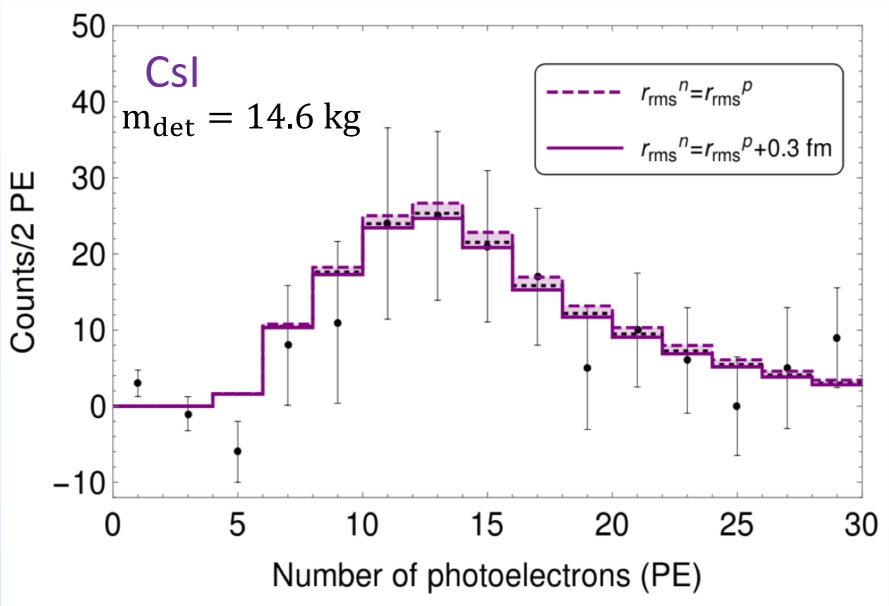
Aristizabal Sierra, JL and Marfatia, JHEP 1906, 141 (2019)



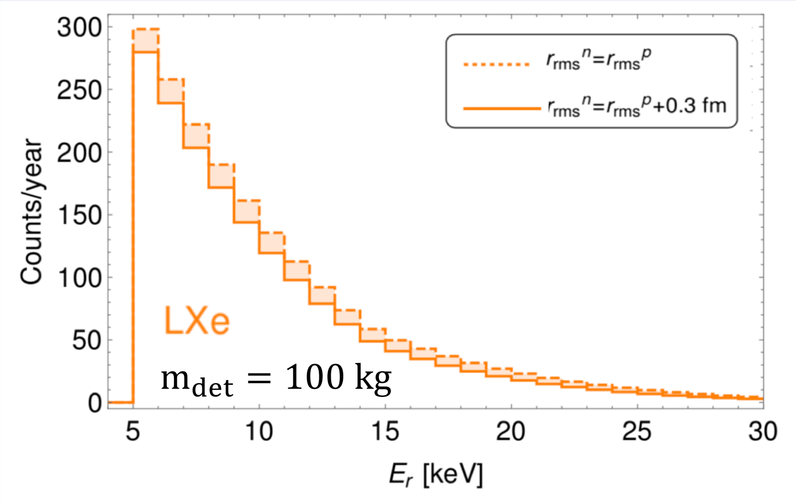
$$\mathcal{U}_H = \left| F_H^2(q^2)|_{r_{\rm rms}^n = r_{\rm rms}^p} - F_H^2(q^2)|_{r_{\rm rms}^n = r_{\rm rms}^p + 0.3\,{\rm fm}} \right| \times 100\%$$

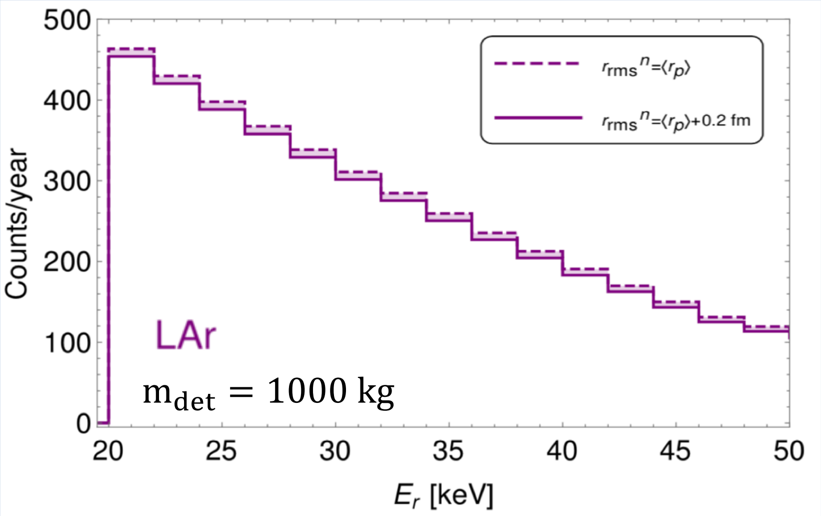
- FF uncertainties are relevant for $q \gtrsim 20$ MeV
- Percentage uncertainties reach maximum at $q \approx 65$ MeV
- Size of the uncertainties do not depend on the FF parameterization chosen

Current data

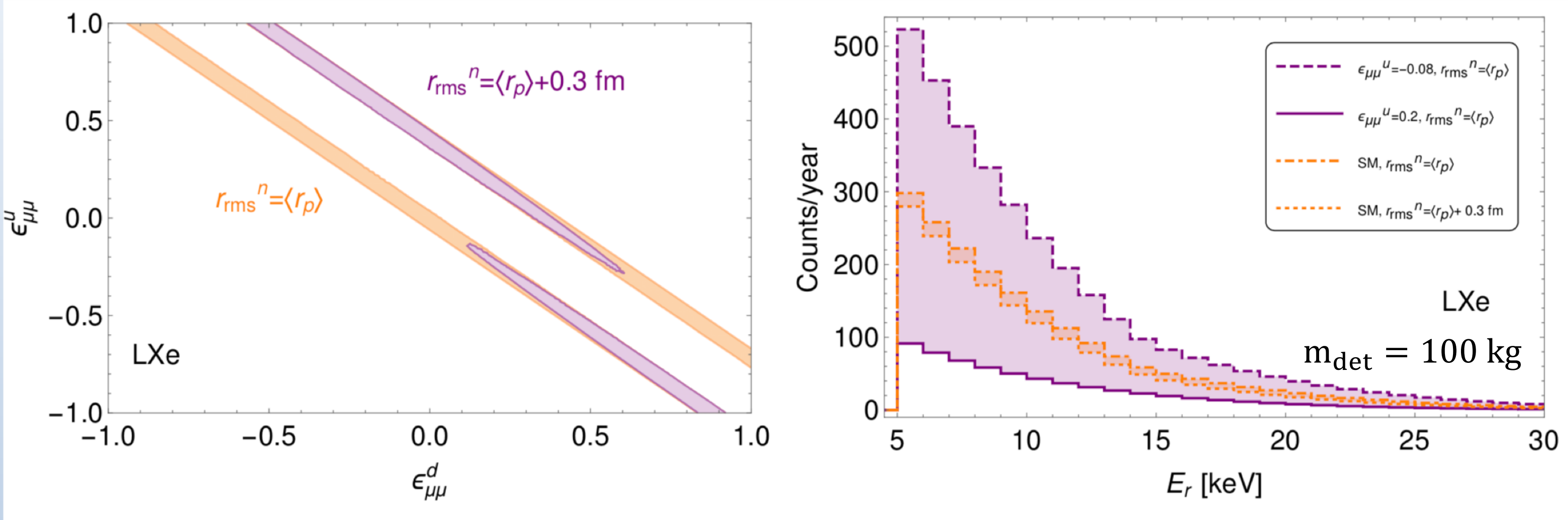


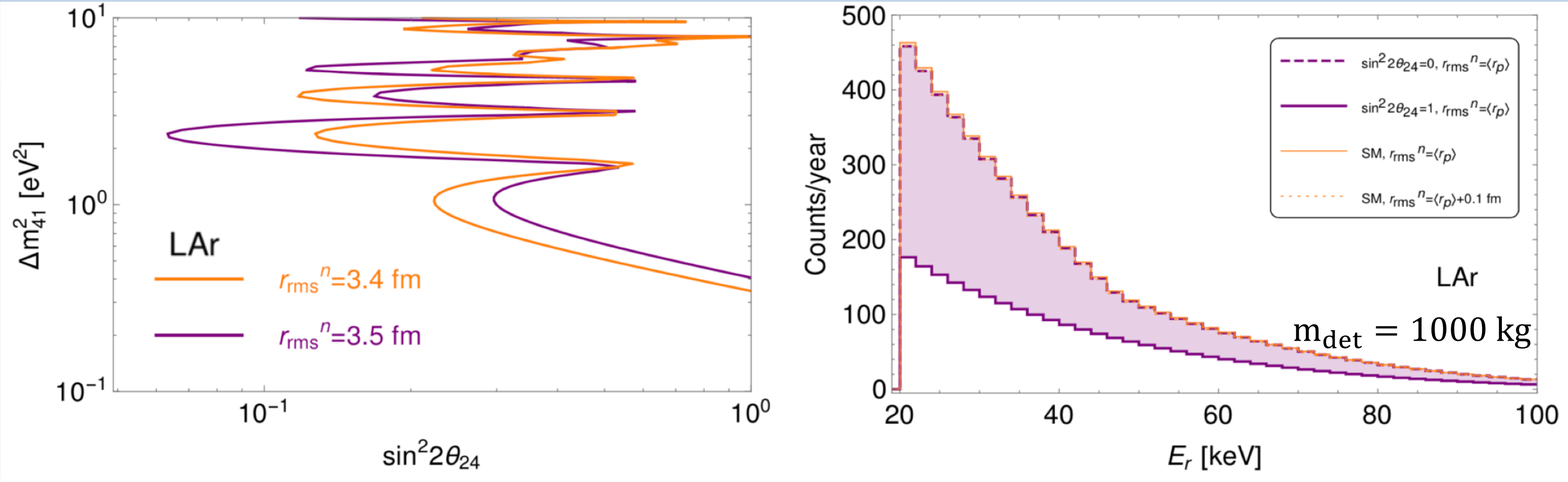
Future upgrade





Impact on New physics

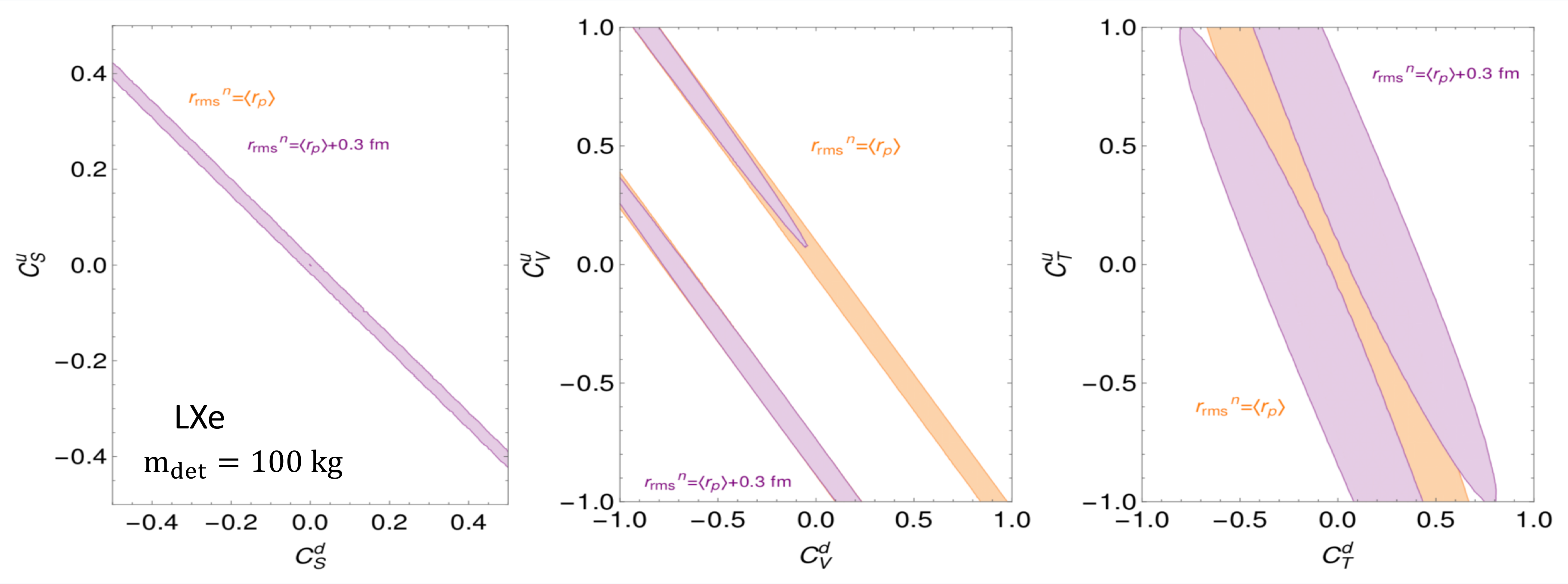




Neutrino Generalized Interactions

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

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



- 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 experiments using the reactor or solar neutrinos.

- New physics searches are strongly affected by FF uncertainties.

Thank you!

Backup slides

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

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

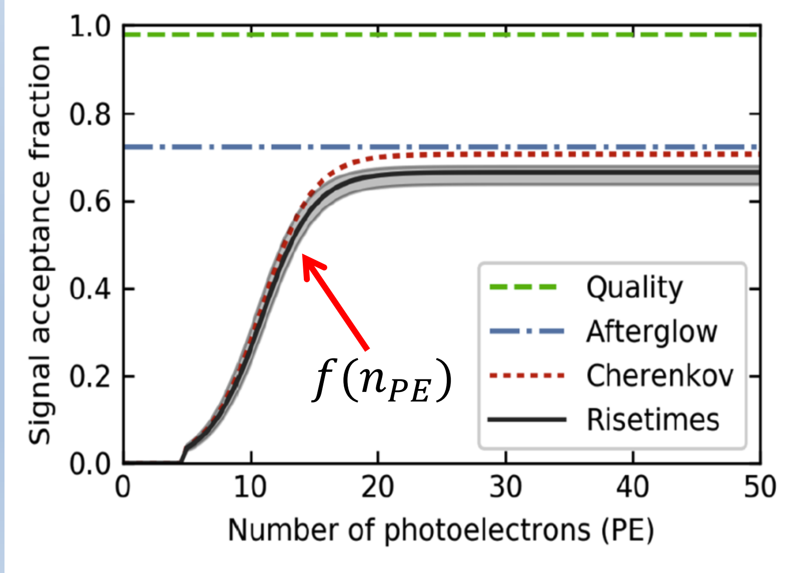
$N_{POT} = 1.76 \times 10^{23}$ is the total number of protons delivered to the target

$L = 19.3$ 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"

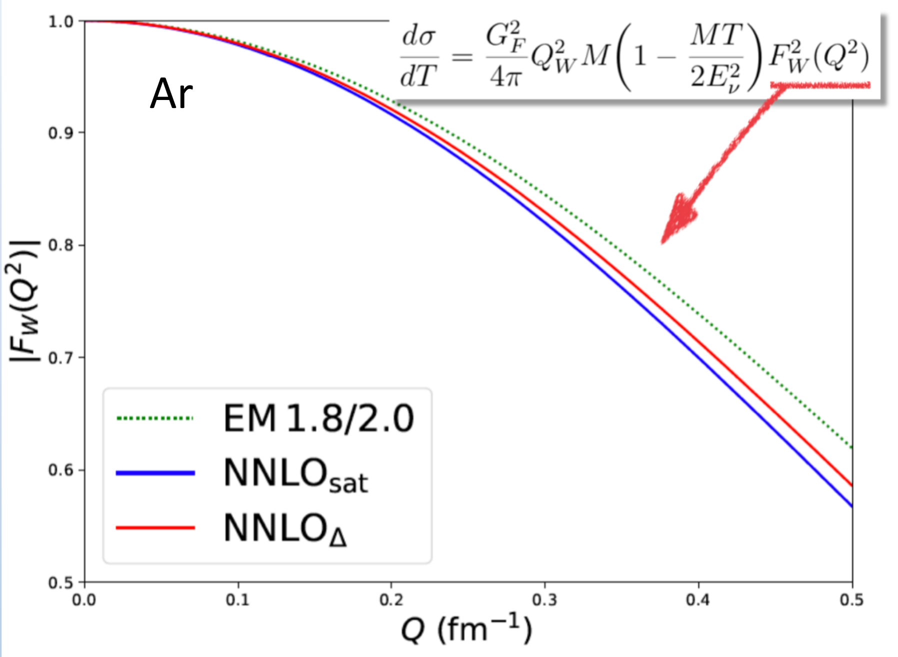
$$n_{\mathrm{PE}} = 1.17 \left(\frac{E_r}{\mathrm{keV}} \right)$$



COHERENT Collaboration, Science (2017)

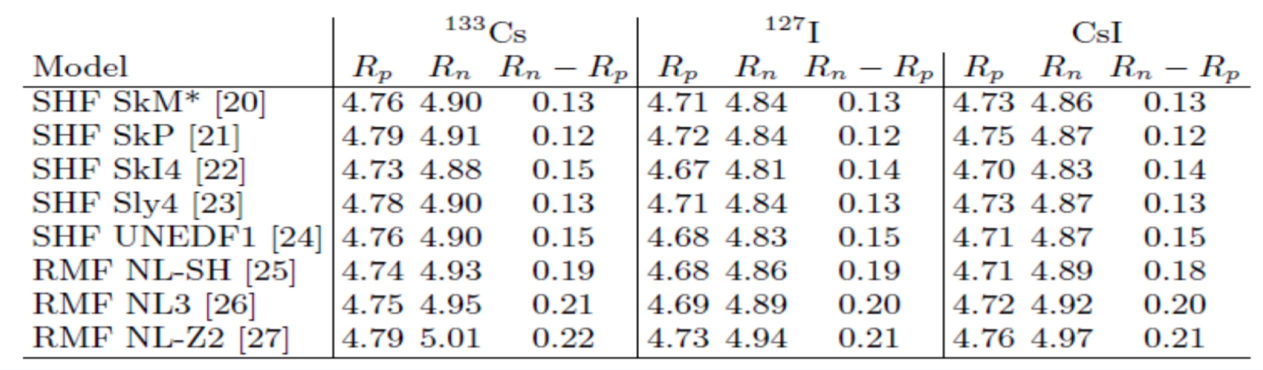
Theoretical predictions

From Gaute Hagen



$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} Q_W^2 M \left(1 - \frac{MT}{2E_\nu^2}\right) \underline{F_W^2(Q^2)}$$

Cadeddu et al. Phys. Rev. Lett. 108, 112502 (2012)



	^{133}Cs			^{127}I			CsI		
Model	R_p	R_n	$R_n - R_p$	R_p	R_n	$R_n - R_p$	R_p	R_n	$R_n - R_p$
SHF SkM* [20]	4.76	4.90	0.13	4.71	4.84	0.13	4.73	4.86	0.13
SHF SkP [21]	4.79	4.91	0.12	4.72	4.84	0.12	4.75	4.87	0.12
SHF SkI4 [22]	4.73	4.88	0.15	4.67	4.81	0.14	4.70	4.83	0.14
SHF Sly4 [23]	4.78	4.90	0.13	4.71	4.84	0.13	4.73	4.87	0.13
SHF UNEDF1 [24]	4.76	4.90	0.15	4.68	4.83	0.15	4.71	4.87	0.15
RMF NL-SH [25]	4.74	4.93	0.19	4.68	4.86	0.19	4.71	4.89	0.18
RMF NL3 [26]	4.75	4.95	0.21	4.69	4.89	0.20	4.72	4.92	0.20
RMF NL-Z2 [27]	4.79	5.01	0.22	4.73	4.94	0.21	4.76	4.97	0.21