Coherent neutrino scattering and quenching factor measurement

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In collaboration w/ Hongkai Liu and Danny Marfatia

arXiv: 2104.01811, Phys. Rev. D 104, 015005 (2021)
arXiv: 2202.10622, accepted as a Letter in PRD

NuFact 2022: 23rd International Workshop on Neutrinos from Accelerators
Cliff Lodge@Snowbird, 8/4/2022

Outline

- Introduction to CEvNS
- Measurement of Ge quenching factor
- CEvNS from reactor antineutrinos
- Summary

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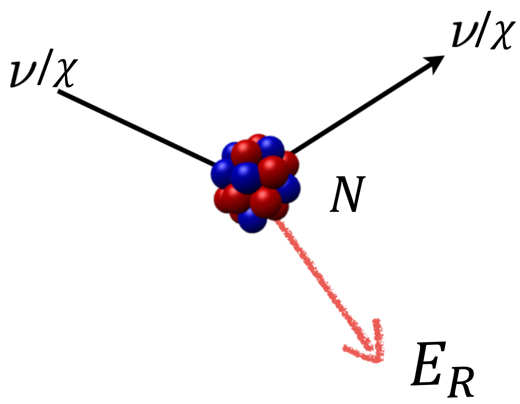
Nuclear recoil



- Dark matter direct detection
- Coherent Elastic ν-Nucleus Scattering (CEνNS)

Moment transfer → $q = \sqrt{2ME_R} \lesssim 1/R$ ← Nuclear radius

Nuclear recoil energy $E_R \leq \frac{2E_\nu^2}{M+2E_\nu} \sim O(1)$ keV for $E_\nu < 50$ MeV

DM direct detection experiments → detection thresholds of $O(1)$ keV

CEνNS experiments

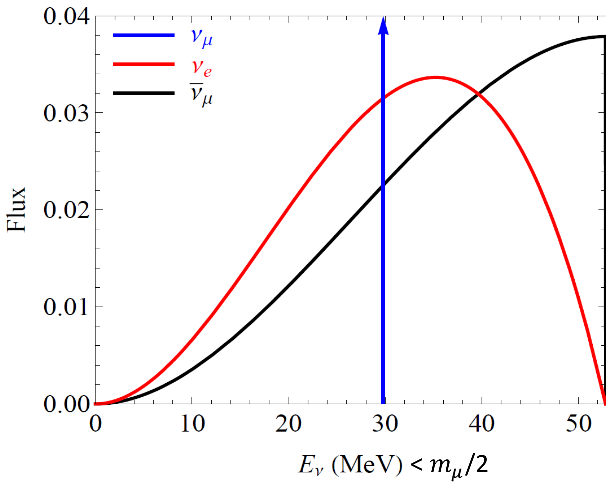
- πDAR source @ SNS

COHERENT first observed CEνNS in 2017 at the 6.7σ CL with a CsI detector

COHERENT, Science 357,1123 (2017)

Later confirmed in 2020 at more than 3σ CL with Ar detector

COHERENT, PRL 126, 012002 (2021)



- Reactor antineutrino source

CONNIE uses a Si detector with 0.1 keV_{ee} threshold

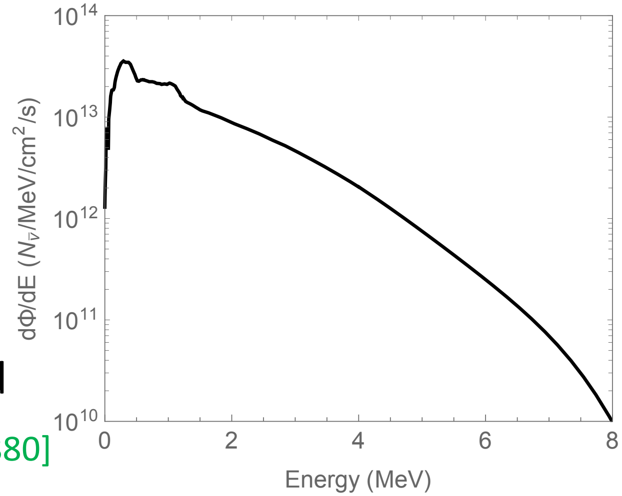
CONNIE, PRD 100, 092005 (2019)

CONUS uses a Ge detector with 0.3 keV_{ee} threshold

CONNIE, PRL 126, 041804 (2021)

NCC-1701 uses a Ge detector with 0.2 keV_{ee} threshold

Colaresi at al. , PRD 104, 072003 (2021) [2108.02880]
Colaresi at al. , arXiv: 2202.09672



CEνNS spectrum

- Differential cross section

$$\frac{d\sigma_{SM}}{dE_R} = \frac{G_F^2 M}{4\pi} q_W^2 \left(1 - \frac{M E_R}{2E_\nu^2}\right) F^2(\mathfrak{q})$$

- Event spectrum

$$\frac{dR}{dE_R} = N_T \int \frac{d\Phi}{dE_\nu} \frac{d\sigma}{dE_R} dE_\nu$$

Only a small portion of nuclear recoiling energy E_R will go into electronic ionization energy E_I , which is measured.

Quenching factor (QF): $Q \equiv E_I / E_R$

$\frac{dE_R}{dE_I}$

Measured number of events:

$$N_i = t \int_{E_I^i}^{E_I^{i+1}} \eta \frac{dR}{dE_R} \left(\frac{1}{Q} - \frac{E_I}{Q} \frac{dQ}{dE_I} \right) dE_I$$

Lindhard Model

Lindhard, Nielsen, Scharff and Thomsen,
Mat. Fys. Medd. Dan. Vid. Selsk. 33 10 (1963)

$$Q(E_R) = \frac{k\, g(\epsilon)}{1 + k\, g(\epsilon)}\,,$$

$$\text{where } g(\epsilon) = 3\,\epsilon^{0.15} + 0.7\,\epsilon^{0.6} + \epsilon$$

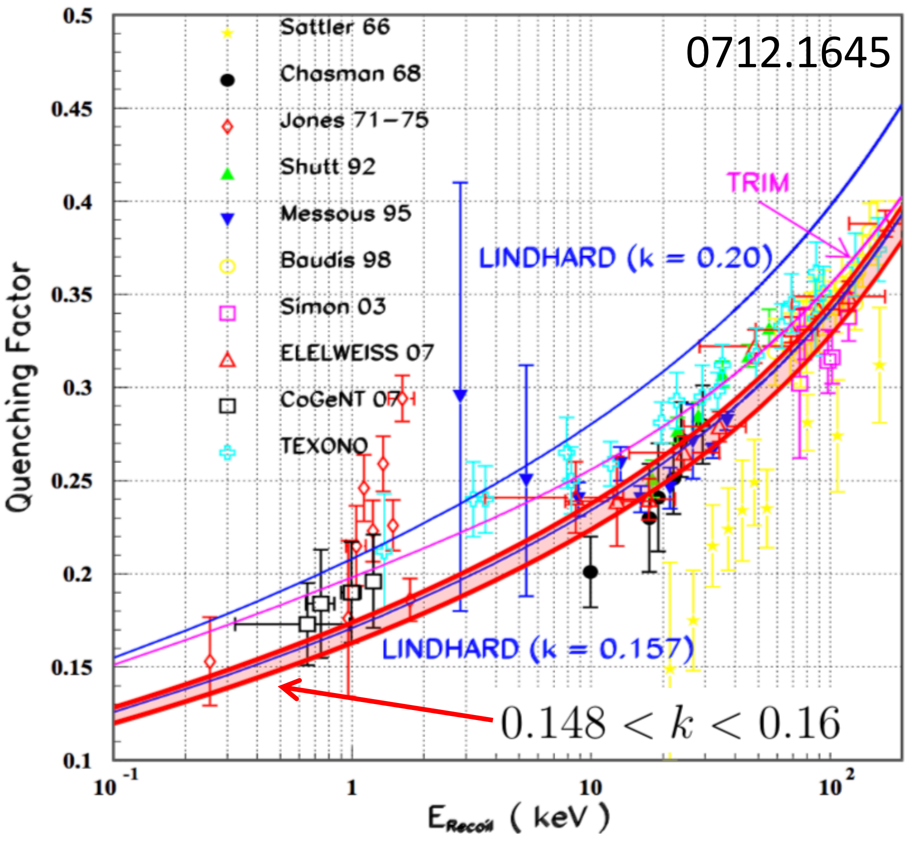
Dimensionless reduced energy

$$\epsilon = 11.5 Z^{-\frac{7}{3}} \left(\frac{E_R}{\mathrm{keV_{nr}}}\right)$$

The slope of electronic stopping power

$$k = 0.1333 Z^{\frac{2}{3}} A^{-\frac{1}{2}}$$

a larger k value leads to larger fraction of total energy going into electron.



Key approximations:

- The atomic binding energy of electrons is negligible.
- Energy transfers to electrons are small relative to energy transfers to atoms.

Sorensen, PRD 91, 083509 (2015) [arXiv: 1412.3028]

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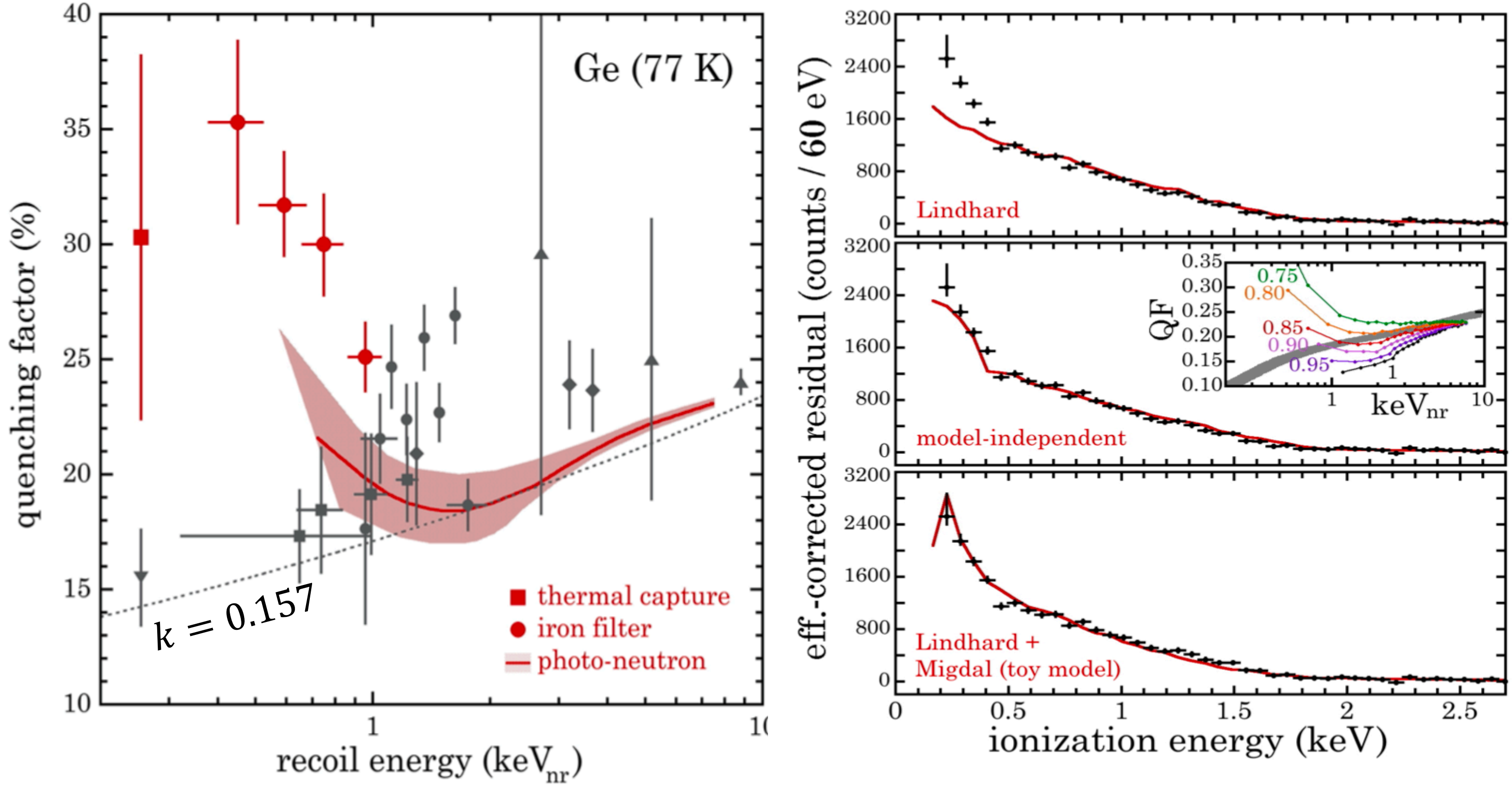
Measurement of Ge QF



The new dataset may be explained by the Lindhard model supplemented with the Migdal effect.

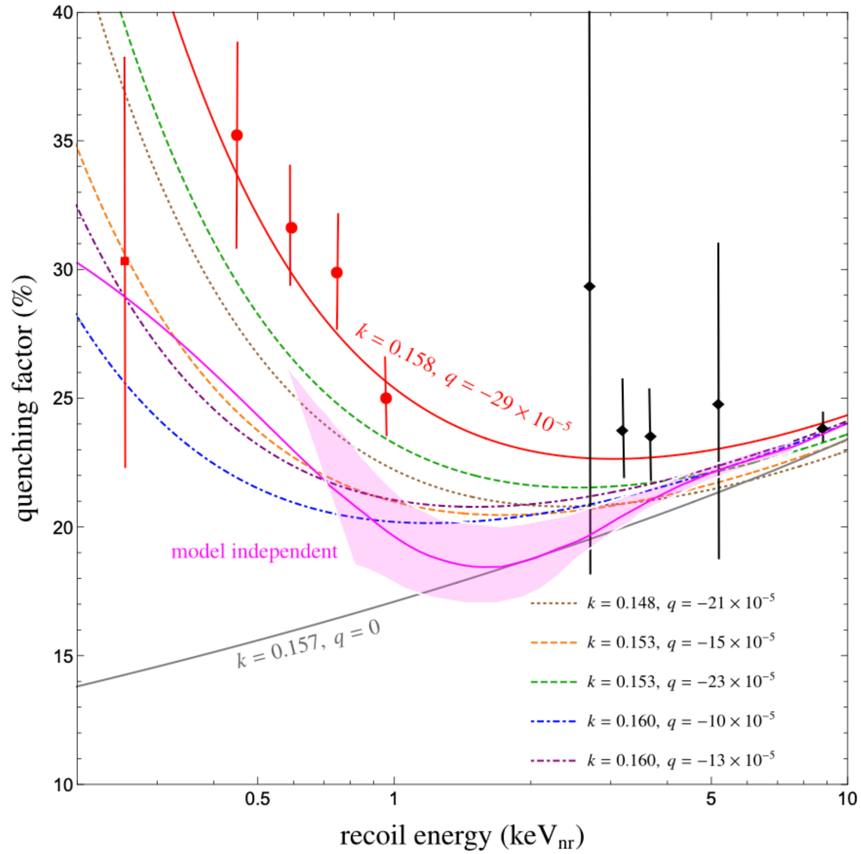
Collar, Kavner, Lewis, PRD 103, 122003 (2021) [arXiv: 2102.10089]

Modified Lindhard Model

$$Q(E_R) = \frac{k\,g(\epsilon)}{1 + k\,g(\epsilon)} - \frac{q}{\epsilon}$$

Sorensen, PRD 91, 083509 (2015)
[arXiv: 1412.3028]

- A small q value has no significant effect at the large recoil energy region.
- A positive q value allows a sharp cutoff in the energy given to electrons.
- A negative q value allows an enhancement in the energy given to electrons.



JL, Liu, Marfatia, PRD 104, 015005 (2021)
[arXiv: 2104.01811]

New Physics in CEvNS

- A light vector Z'

$$\frac{d\sigma_{SM+Z'}}{dE_R} = \left(1 - \frac{q_{Z'}}{q_W}\right)^2 \frac{d\sigma_{SM}}{dE_R}$$

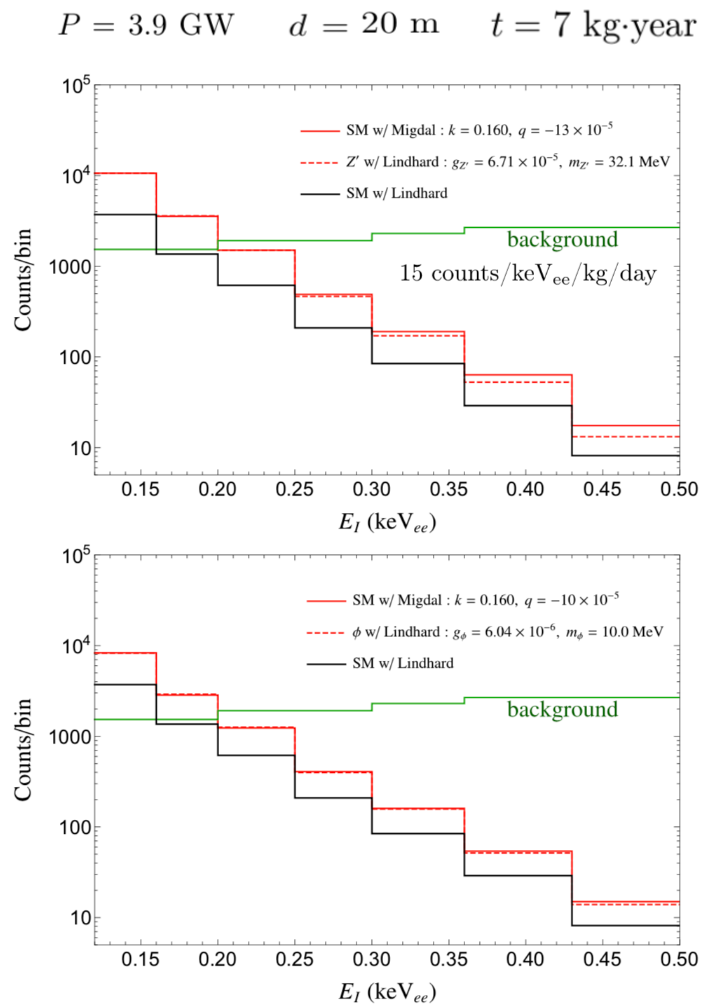
$$q_{Z'} = \frac{3\sqrt{2}\,(N+Z)\,g'^2}{G_F\,(2ME_R + M_{Z'}^2)}$$

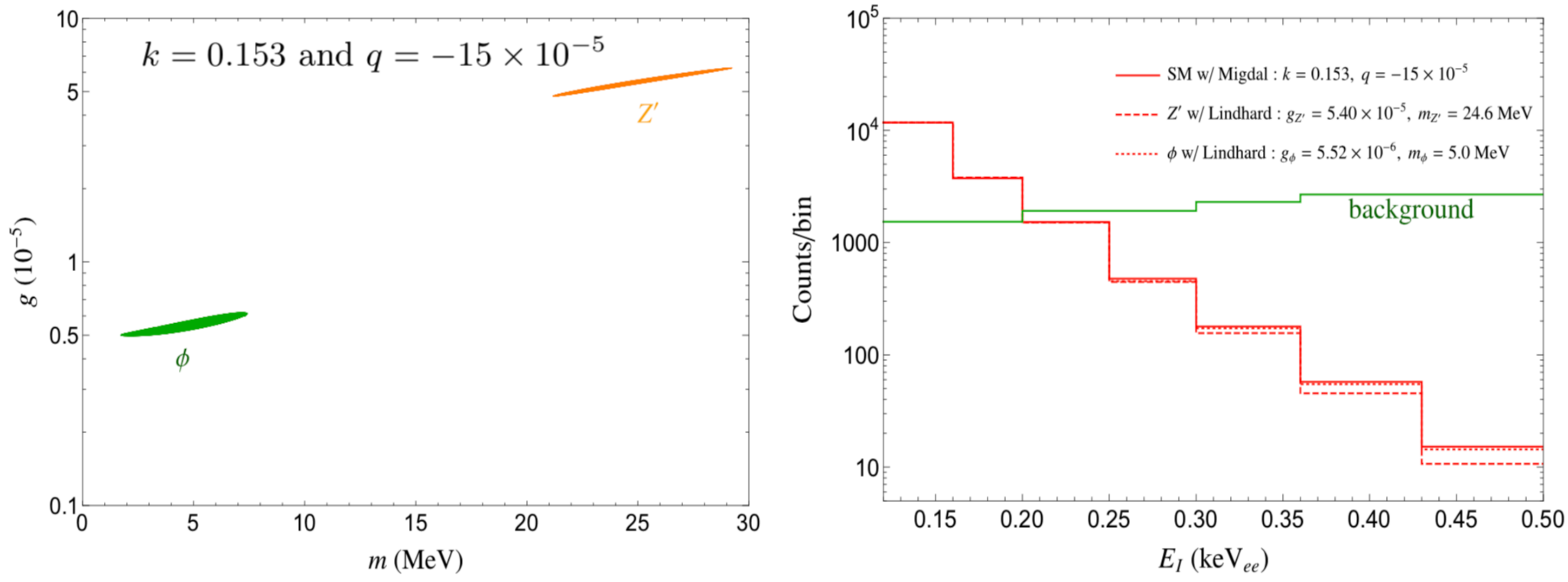
- A light scalar ϕ

$$\frac{d\sigma_{SM+\phi}}{dE_R} = \frac{d\sigma_{SM}}{dE_R} + \frac{d\sigma_\phi}{dE_R}$$

$$\frac{d\sigma_\phi}{dE_R} = \frac{G_F^2}{4\pi} q_\phi^2 \frac{2ME_R}{E_\nu^2} M F^2(\mathfrak{q})$$

$$q_\phi = \frac{(14N + 15.1Z)\,g_\phi^2}{\sqrt{2}G_F\,(2ME_R + M_\phi^2)}$$





- Both the light Z' and scalar cases with the standard Lindhard model can fit the SM spectrum for a given set of QF parameters k and q.

- This will lead to confusion in determining the nature of new physics.

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Suggestive evidence for coherent elastic neutrino-nucleus scattering from reactor antineutrinos

arXiv: 2202.09672

J. Colaresi[1], J.I. Collar[2,*] T.W. Hossbach[3], C.M. Lewis[2], and K.M. Yocum[1]
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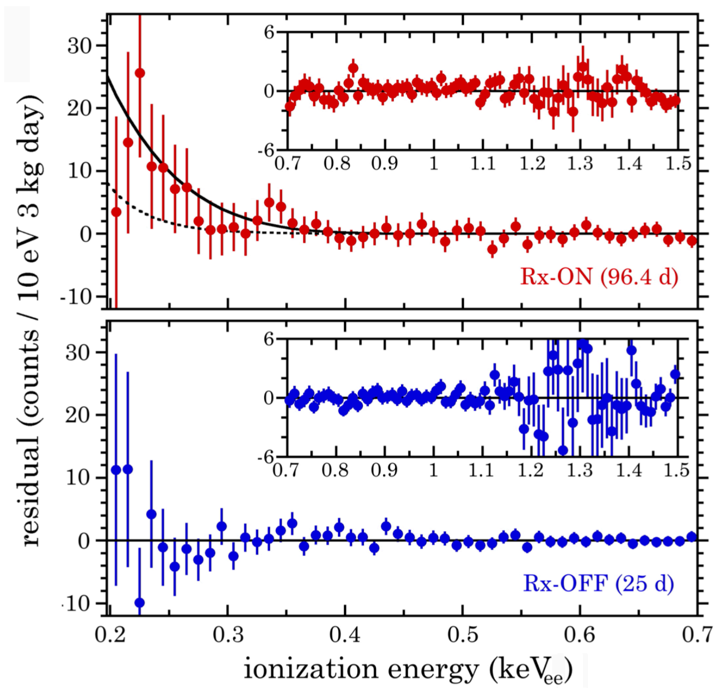
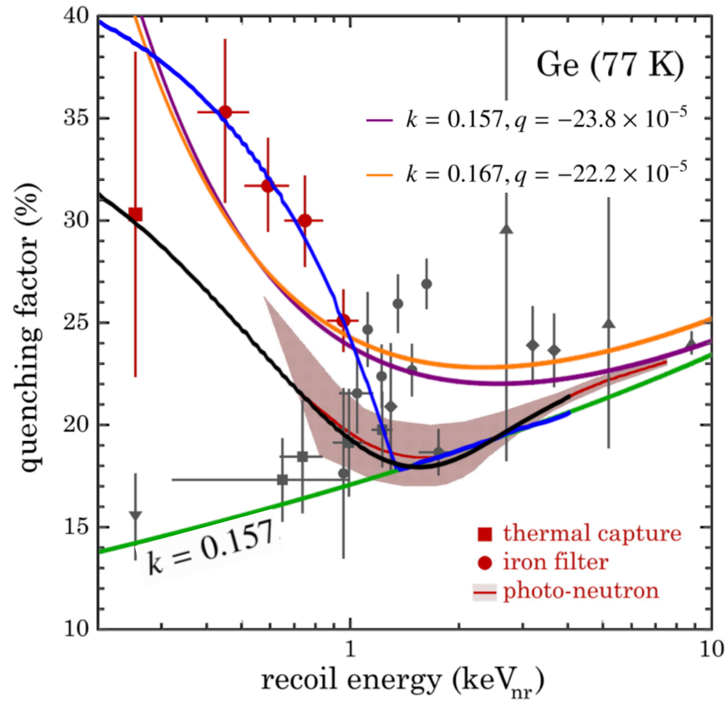
[2] *Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA and*
[3] *Pacific Northwest National Laboratory, Richland, Washington 99354, USA*
(Dated: February 22, 2022)

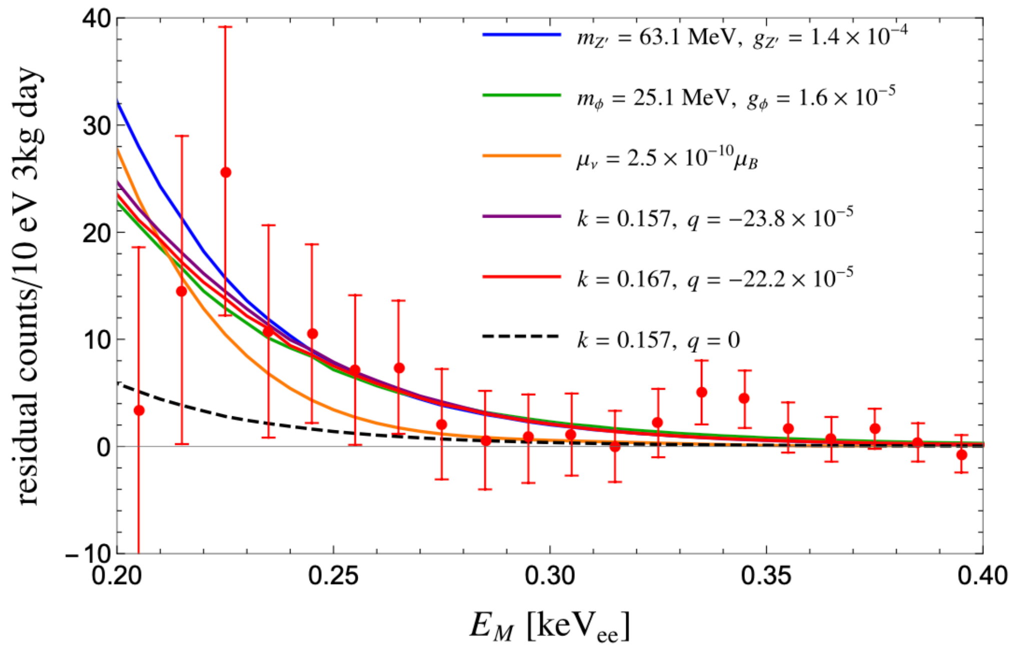


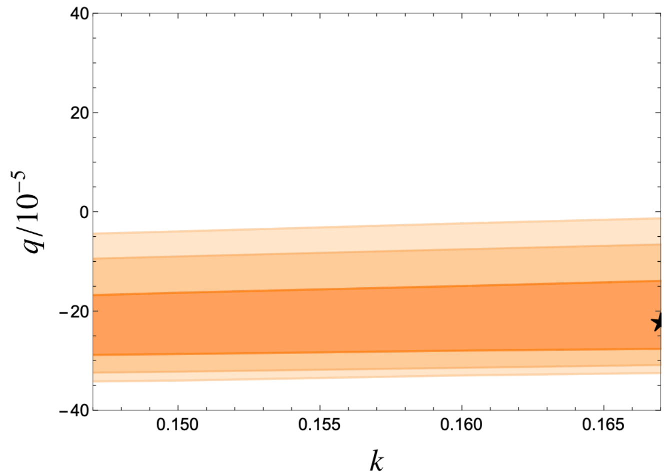


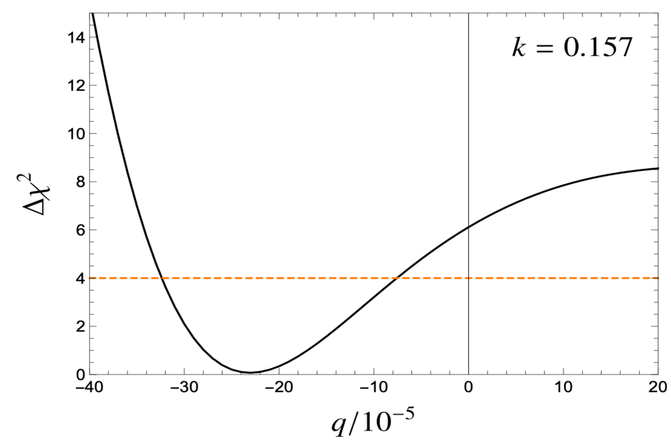
Solid (dotted) line shows the SM CEvNS prediction for the iron filter (Lindhard) QF.

Blue (black) line are based on the data from the iron filter (photo-neutron) measurement.

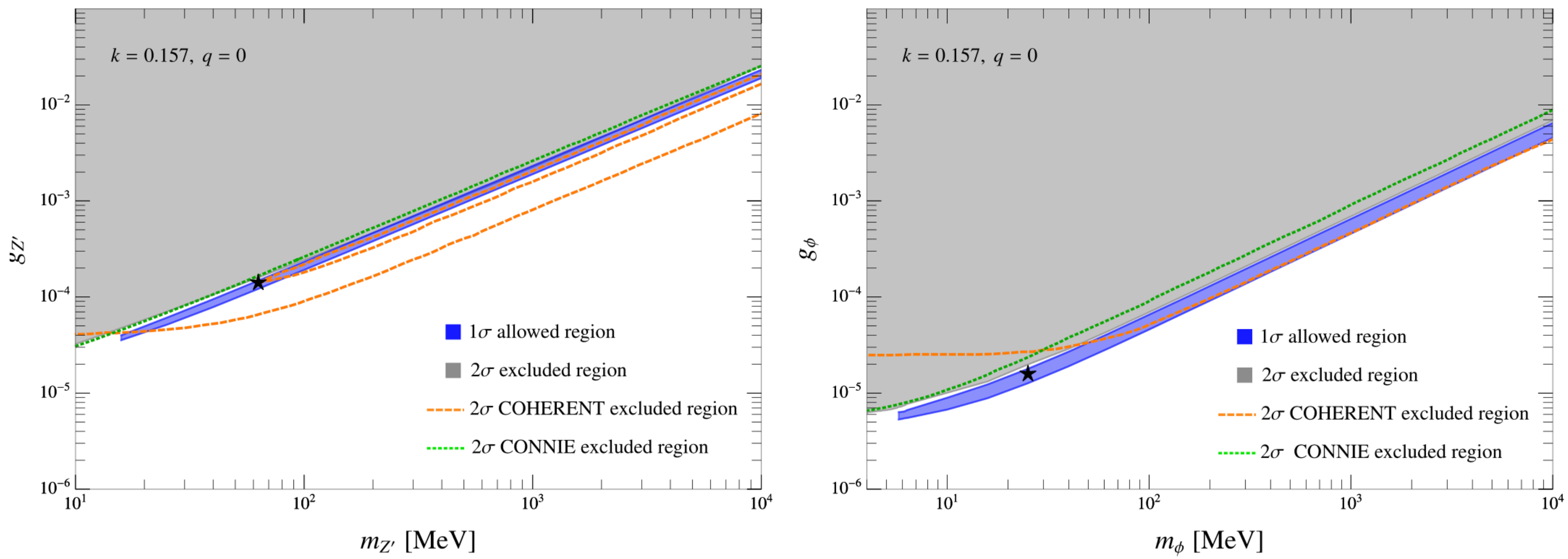
Quenching factor sensitivity







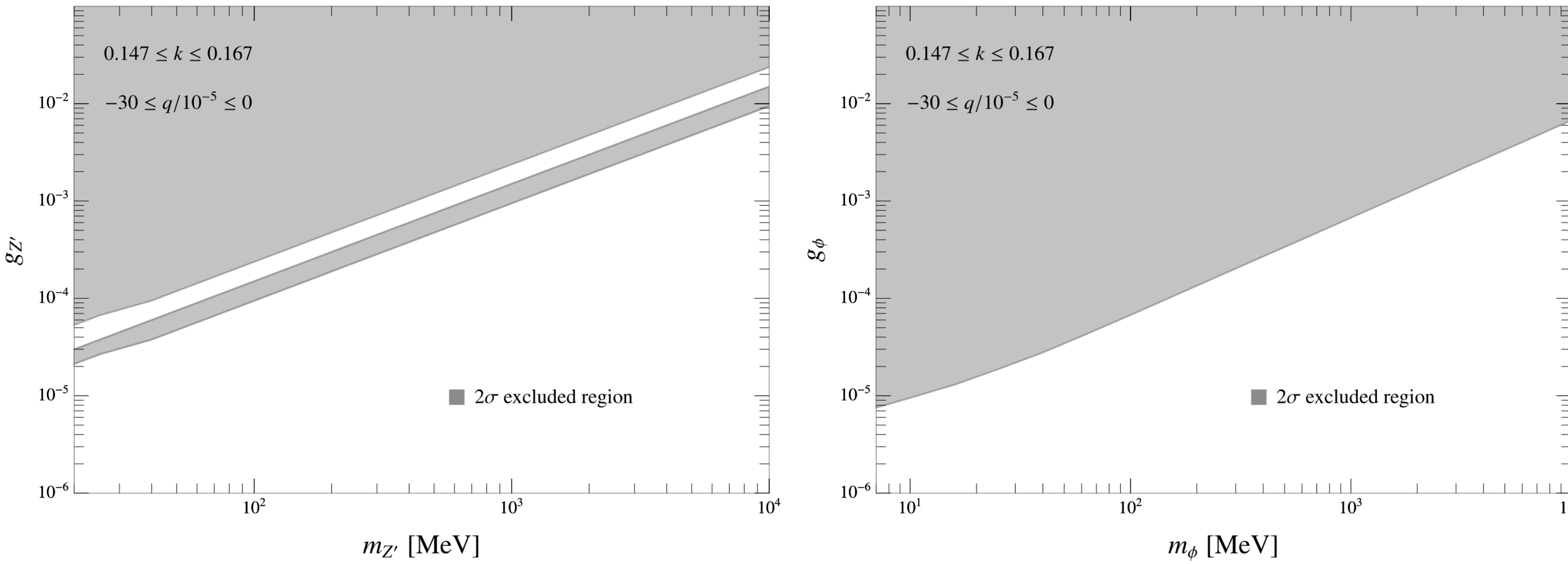
New Physics



- Assume the standard Lindhard QF model is valid.
- 1σ allowed region of light Z' is also allowed by COHERENT due to

$$q_{Z'} = 2q_W \Longrightarrow \frac{g_{Z'}}{m_{Z'}} = \sqrt{\frac{\sqrt{2}G_F\left[N - (1 - 4\sin^2\theta_W)Z\right]}{3(N+Z)}}$$

New Physics



- Marginalize over the (k,q) of the modified Lindhard model.
- Constraints are qualitatively affected by the QF model.

Summary

- Recent direct QF measurement in Ge indicates a departure from the standard Lindhard model at low energies.
- This deviation can be parameterized by a negative q in the modified Lindhard model.
- NCC-1701 data provide an independent probe of Ge quenching factor, and the best-fit point is consistent with the direct QF measurements.
- A precise measurement of the QF is essential to detect new physics at CEvNS.

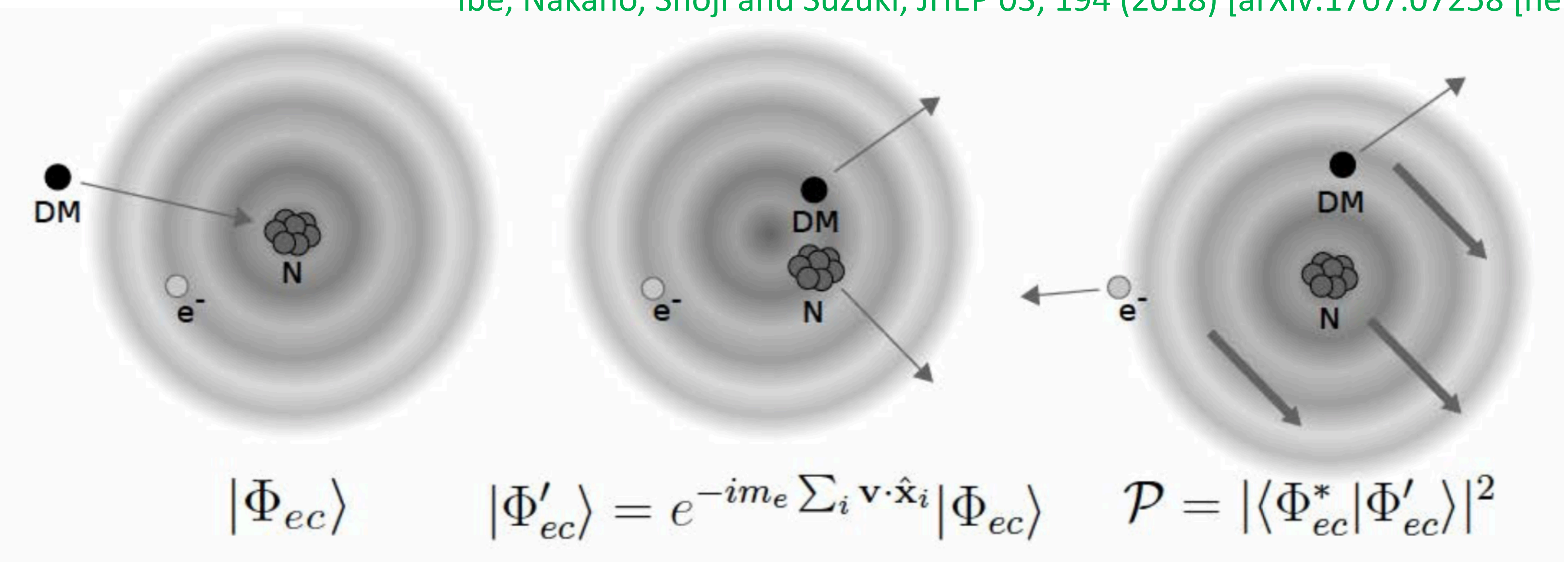
Thanks!

Backup slides

Migdal Effect

"...it is usually assumed that the atomic electrons around the recoil nucleus immediately follow the motion of the nucleus. However, it takes some time for the electrons to catch up, which causes ionization and excitation of the recoil atom..."

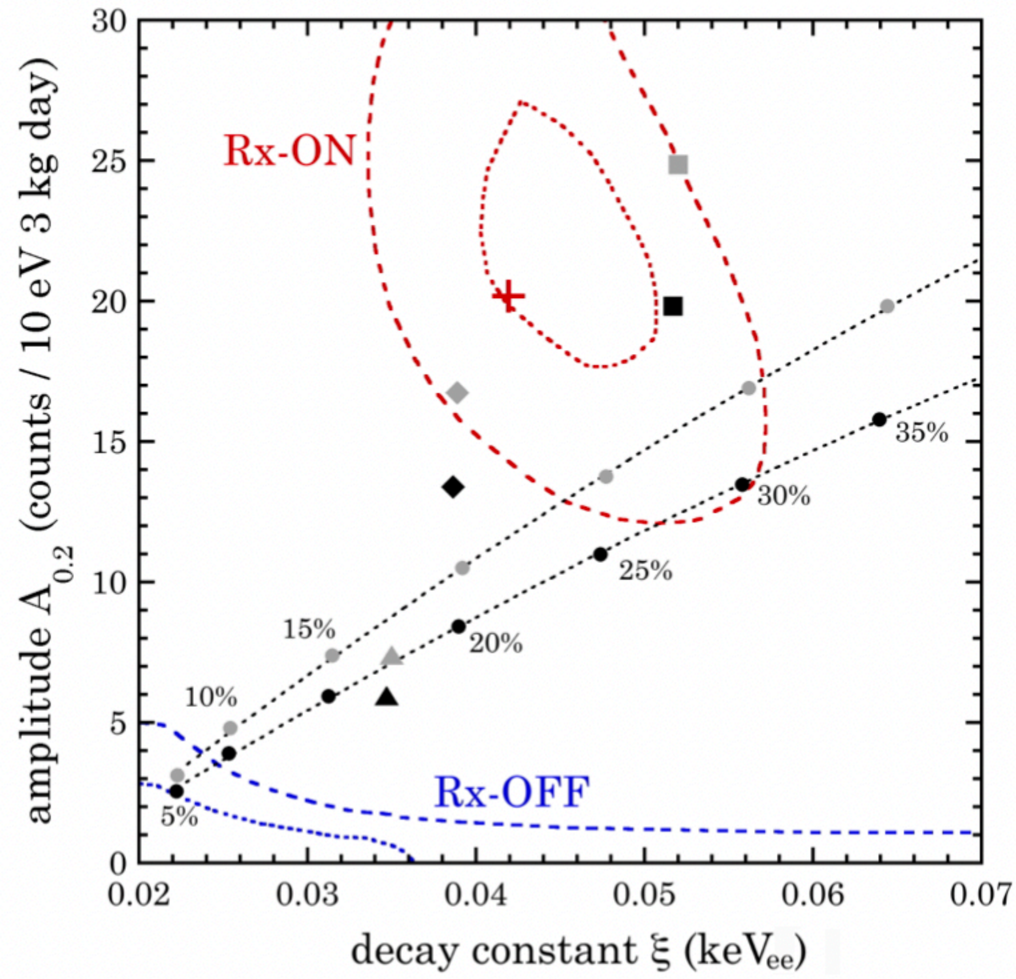
Migdal, J.Phys.(USSR) 4, 449 (1941).
Ibe, Nakano, Shoji and Suzuki, JHEP 03, 194 (2018) [arXiv:1707.07258 [hep-ph]].



A value of P =50% are needed to obtain agreement of the data, being a factor of approximately seven above the integrated ionization probabilities calculated for Migdal shakeoff from atomic germanium in 1707.07258

Collar, Kavner, Lewis, PRD 103, 122003 (2021) [arXiv: 2102.10089]

CEvNS Signal H_1 $A_{0.2}\ e^{-(E-0.2)/\xi}$



arXiv: 2202.09672

Fit Results

scenarios	k	$q/10^{-5}$	model parameters	$\chi^2_{\rm min}/\text{d.o.f.}$
SM w/ standard Lindhard	0.157	0	-	14.34/19
SM w/ modifed Lindhard w/ fixed k	0.157	-23.8	-	8.28/18
SM w/ modified Lindhard w/ $0.147 \leq k \leq 0.167$	0.167	-22.2	-	8.14/17
light Z'	0.157	0	$m_{Z'} = 63.1$ MeV, $g_{Z'} = 1.4 \times 10^{-4}$	9.09/17
light scalar	0.157	0	$m_\phi = 25.1$ MeV, $g_\phi = 1.6 \times 10^{-5}$	7.77/17
neutrino magnetic moment	0.157	0	$\mu_\nu = 2.5 \times 10^{-10} \mu_B$	11.71/18

$$\frac{dR}{dE_M} = \frac{\int_0^\infty G(E_M, E_I, \sigma^2)\, \frac{dR}{dE_I} dE_I}{\int_0^\infty G(E_M, E_I, \sigma^2) dE_I}$$

$$N_i = t \int_{E_M^i}^{E_M^{i+1}} \frac{dR}{dE_M} dE_M \qquad \chi^2 = \sum_i \left[\frac{N^i_{\rm exp} - N^i_{\rm th}(1+\alpha)}{\sigma_i} \right]^2 + \left(\frac{\alpha}{\sigma_\alpha} \right)^2$$