Coherent neutrino scattering and Migdal effect on the quenching factor

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Based on Phys. Rev. D 104, 015005 (2021) [arXiv: 2104.01811]

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Outline

- Introduction to CEvNS
- Migdal effect on quenching factor
- Impact on new physics
- Summary

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Coherent Elastic ν-Nucleus Scattering

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

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National Accelerator Laboratory, Batavia, Illinois 60510
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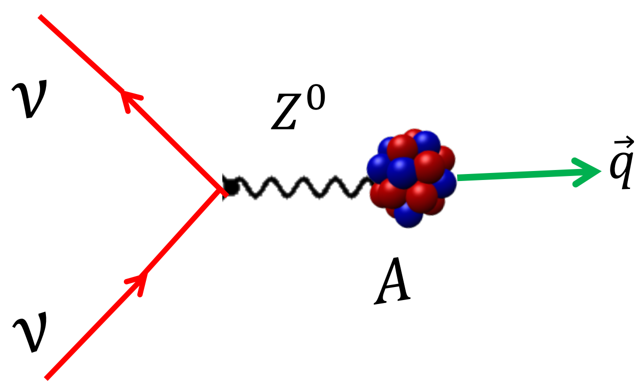
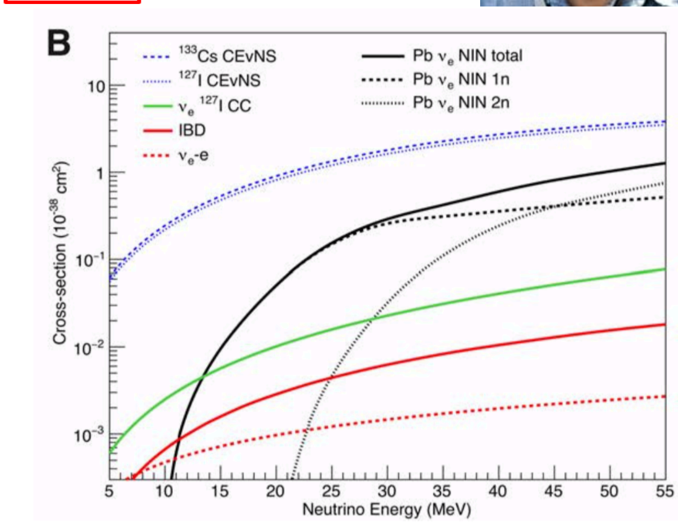
(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \rightarrow \nu + A$ should





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

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

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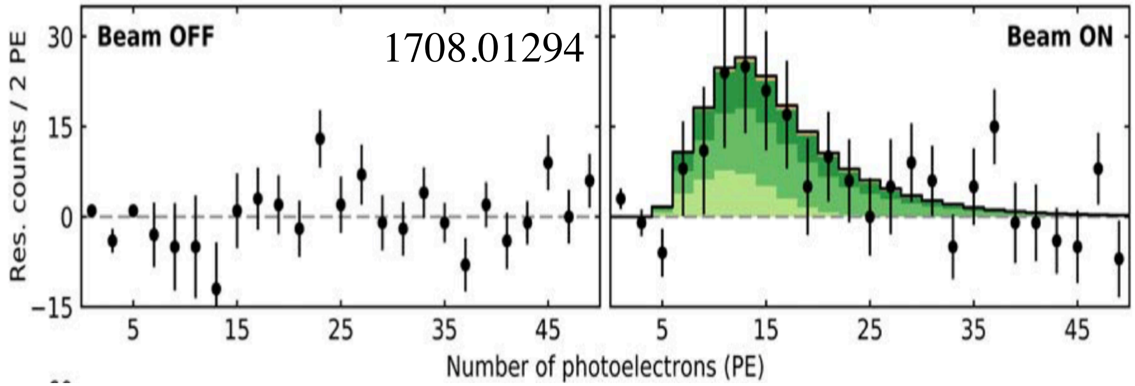
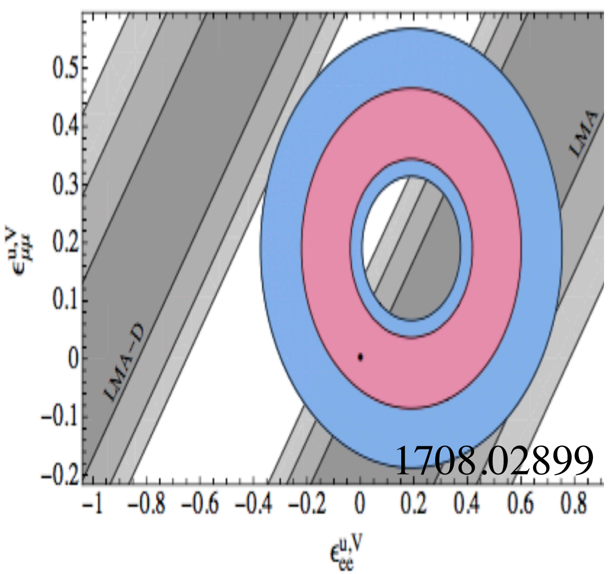
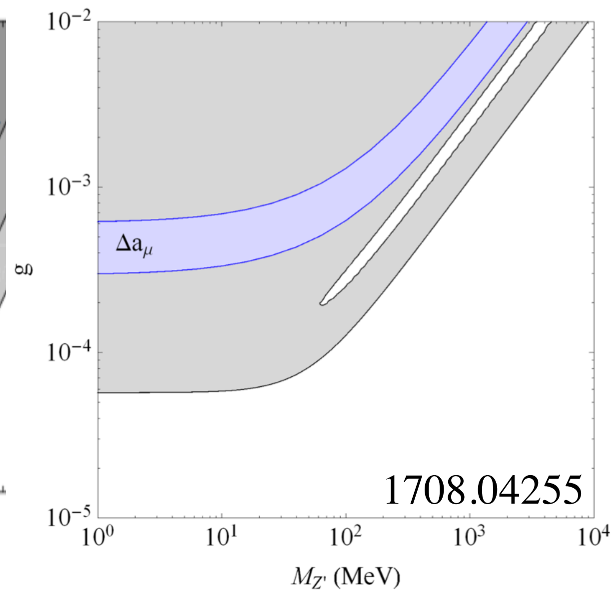


6.7σ CL evidence

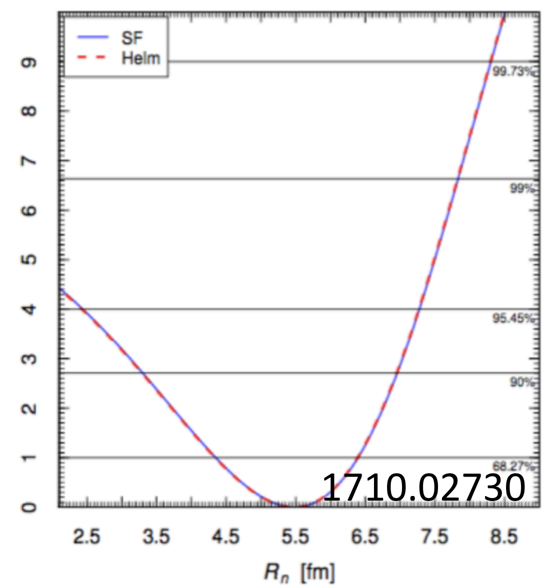
COHERENT Collaboration, Science 357,1123 (2017)



Coloma, Conzalez-Garcia, Maltoni, PRD 96, 115007 (2017)



JL, Marfatia, PLB 775, 54 (2017)



Cadeddu, Giunti, Li, Zhang, PRL 120, 072501 (2018)

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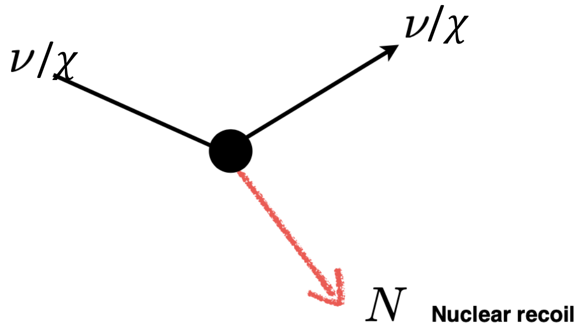


Spectrum

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

Effect charge: $$q_W = N - (1 - 4\sin^2\theta_W)Z$$

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

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

Quenching factor: $$Q \equiv E_I / E_R$$

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

Standard Lindhard Model

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

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

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

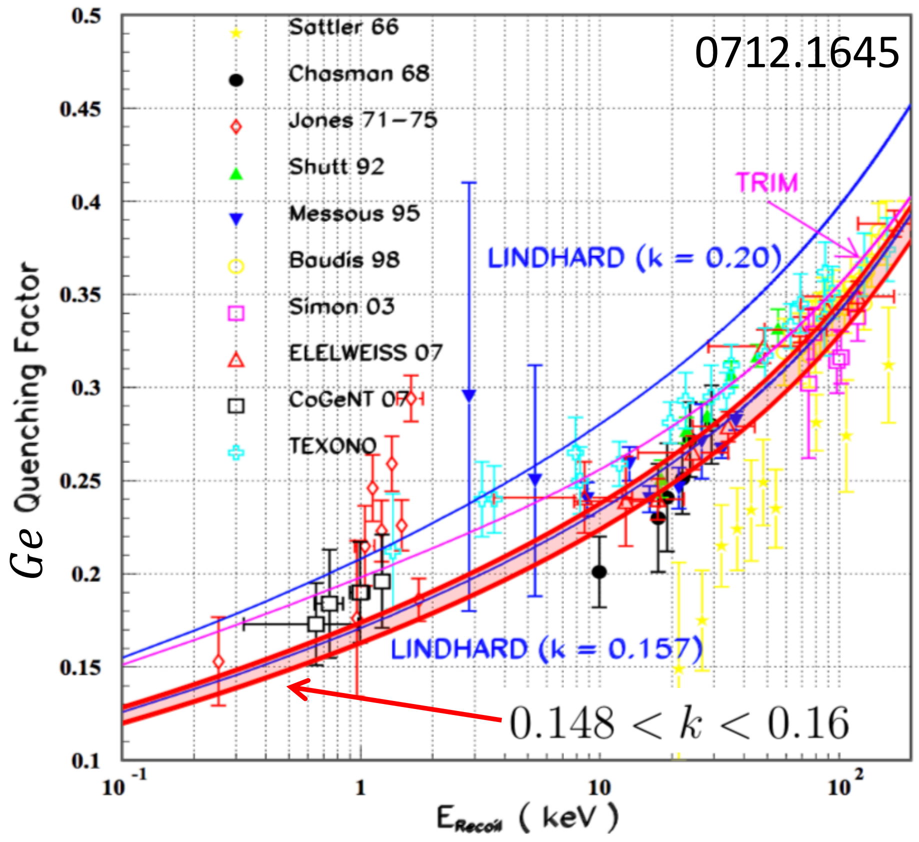
dimensionless reduced energy

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

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.



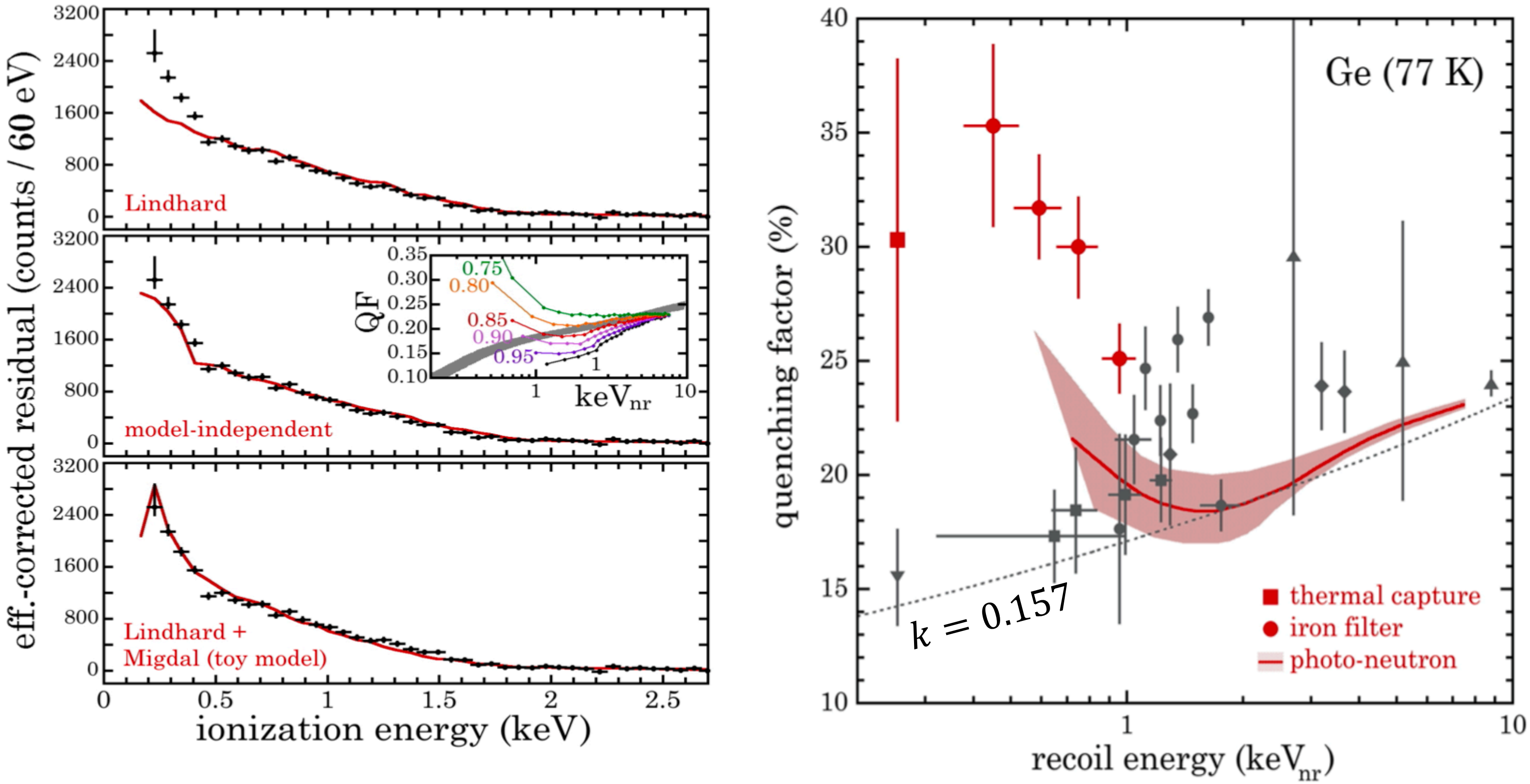
Key approximations:

- 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]

Germanium QF Measurement

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



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

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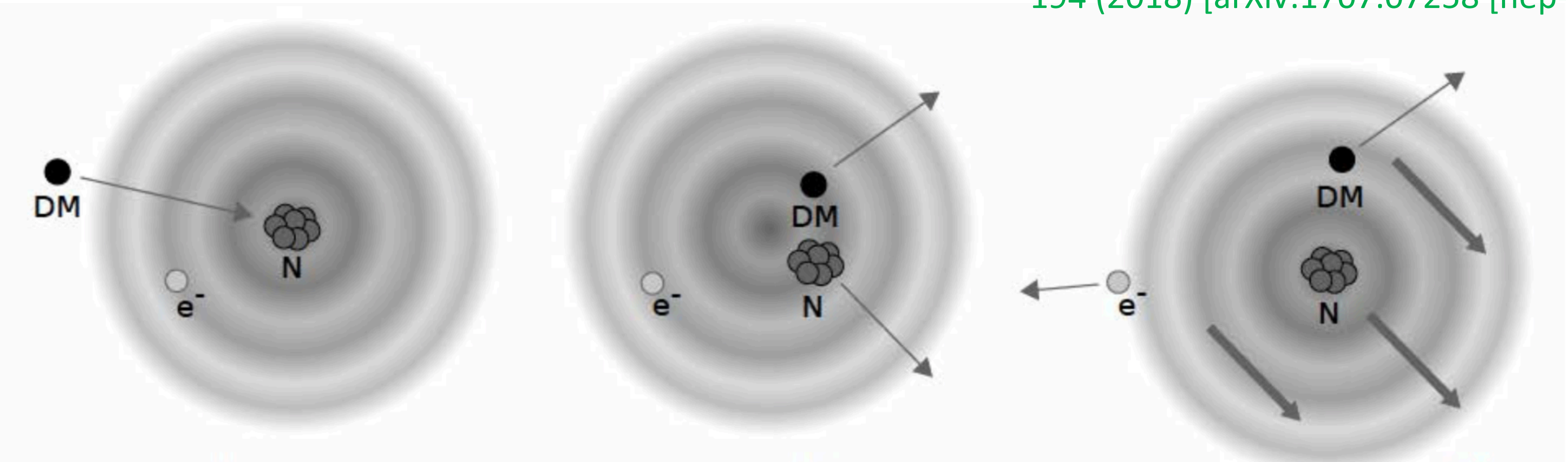
Migdal Effect

Migdal, J.Phys.(USSR) 4, 449 (1941).

"...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..."

Ibe, Nakano, Shoji and Suzuki, JHEP 03, 194 (2018) [arXiv:1707.07258 [hep-ph]].



$$|\Phi_{ec}\rangle \qquad |\Phi'_{ec}\rangle = e^{-im_e \sum_i \mathbf{v}\cdot\hat{\mathbf{x}}_i}|\Phi_{ec}\rangle \qquad \mathcal{P} = |\langle\Phi^*_{ec}|\Phi'_{ec}\rangle|^2$$

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 by 1707.07258

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

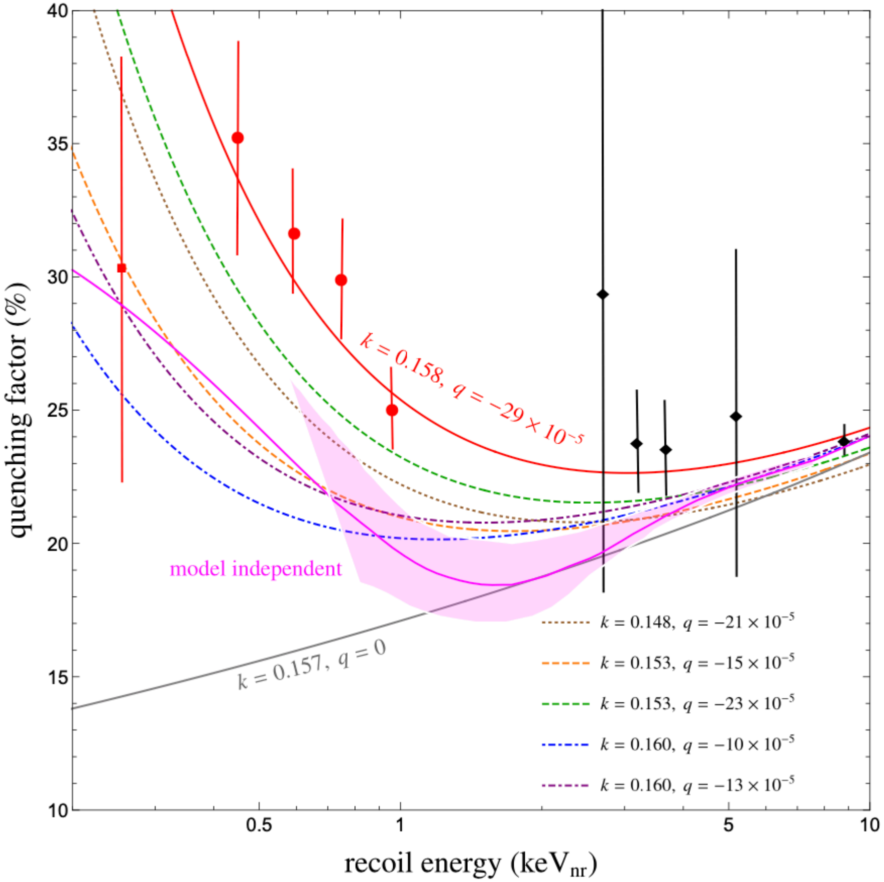
Modified Lindhard Model

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

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

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

- 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.



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New Physics in CEvNS

- A light vector Z'

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

$$\frac{d\sigma_{SM}}{dE_R} = \frac{G_F^2 M}{4\pi} q_W^2 \left(1 - \frac{M E_R}{2E_\nu^2}\right) F^2(\mathfrak{q}) \qquad q_{Z'} = \frac{3\sqrt{2}\,(N+Z)\,g'^2}{G_F\,(2ME_R + M_{Z'}^2)}$$

- A light scalar ϕ

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

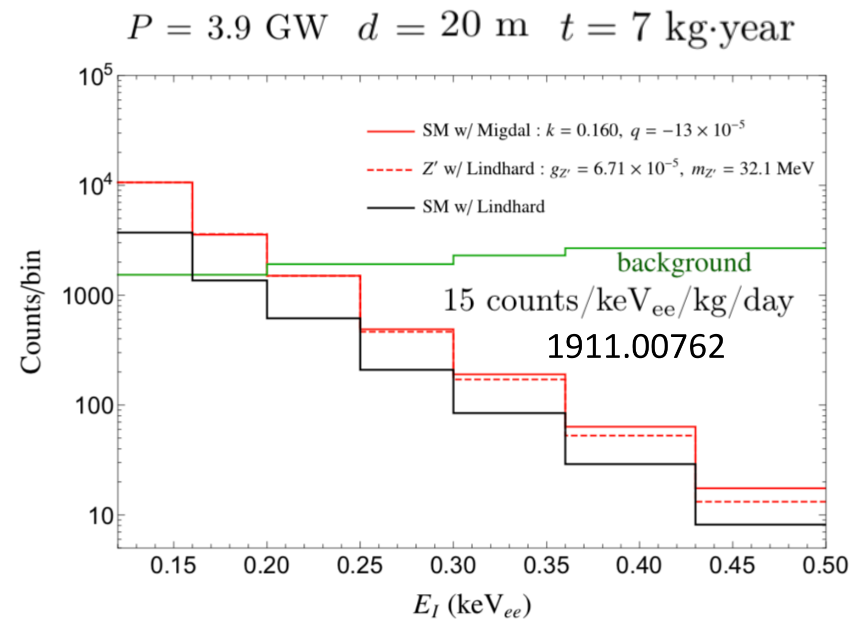
$$\frac{d\sigma_\phi}{dE_R} = \frac{G_F^2}{4\pi} q_\phi^2 \frac{2ME_R}{E_\nu^2} M F^2(\mathfrak{q}) \qquad q_\phi = \frac{(14N + 15.1Z)\,g_\phi^2}{\sqrt{2}G_F\left(2ME_R + M_\phi^2\right)}$$

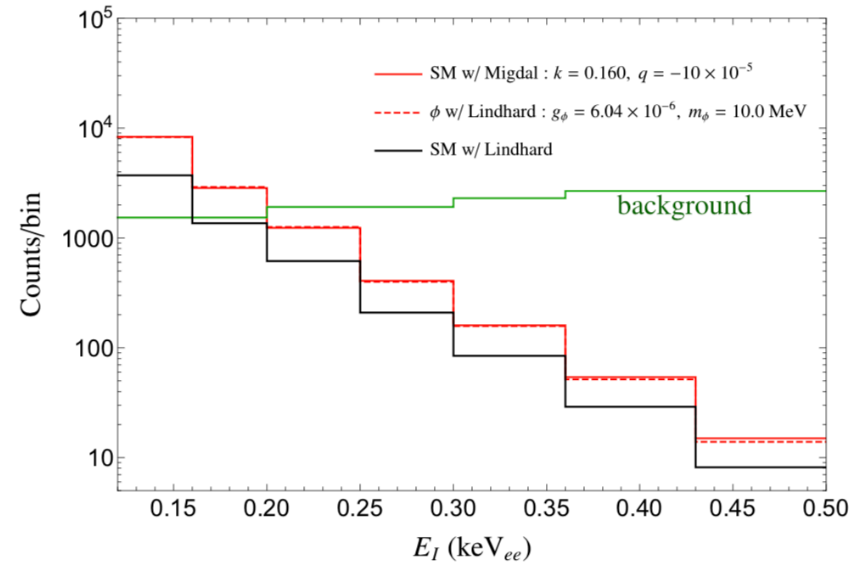
$$\frac{d\Phi}{dE_\nu} = \frac{P}{4\pi d^2 \tilde{\epsilon}} \left(\frac{dN_\nu}{dE_\nu} \right)$$

We simulated SM data with Migdal parameters (k, q), fit the new physics with the standard Lindhard model.

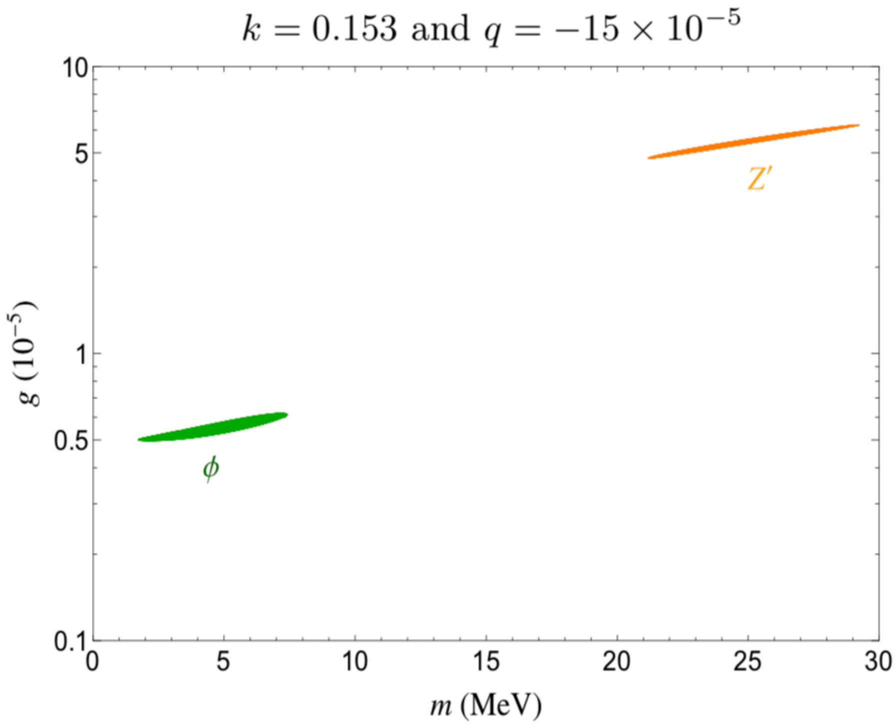
$m_{Z'}/\text{MeV}$	$g_{Z'} \times 10^5$	k	$q \times 10^5$	χ^2_{min}
16.2	4.24	0.148	−21	5.95
24.6	5.40	0.153	−15	1.32
32.1	6.71	0.160	−13	0.81

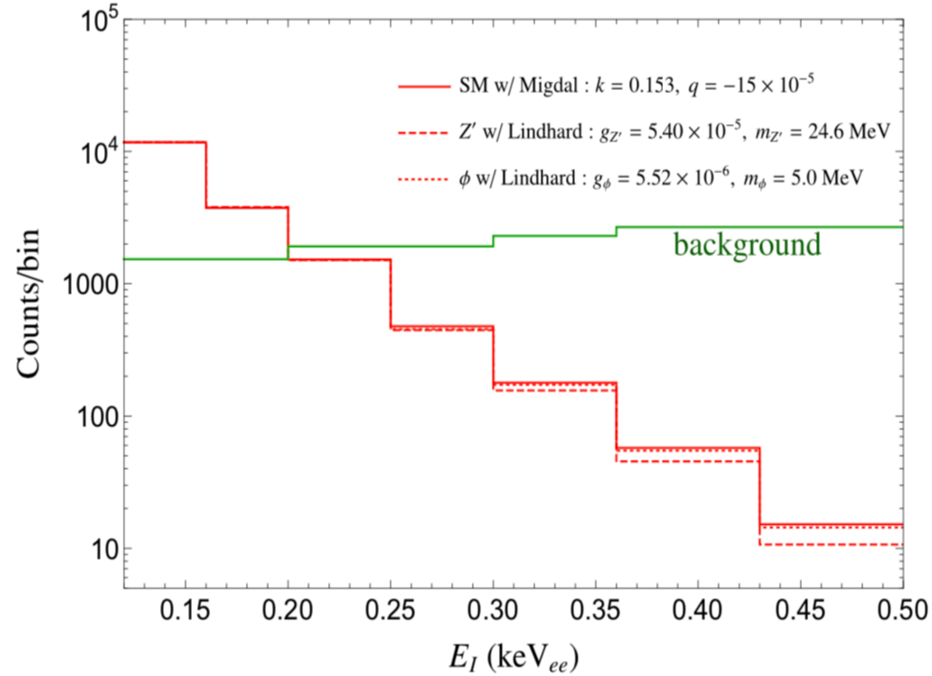
m_ϕ/MeV	$g_\phi \times 10^6$	k	$q \times 10^5$	χ^2_{min}
0.52	6.31	0.153	−23	2.11
5.0	5.52	0.153	−15	0.32
10.0	6.04	0.160	−10	1.46





Both light Z' and scalar with the standard Lindhard model can mimic the SM with the Migdal effect on the quenching factor.





- Both the light Z’ and scalar cases with the standard Lindhard model can fit the SM spectrum for a fixed set of Migdal parameters.

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

Summary

- Recent measurements of the quenching factor in germanium indicate a departure from the standard Lindhard model.

- This deviation can be explained by the Migdal effect on the quenching factor, and parameterized by a negative q in the modified Lindhard model.

- Both light Z′ and scalar can mimic the SM with the Migdal effect. There is a degeneracy between light Z′ and scalar for a given set of Migdal parameters.

- A precise measurement of the quenching factor with low energy thresholds is required to detect new physics at CEvNS

Thanks for your attention!