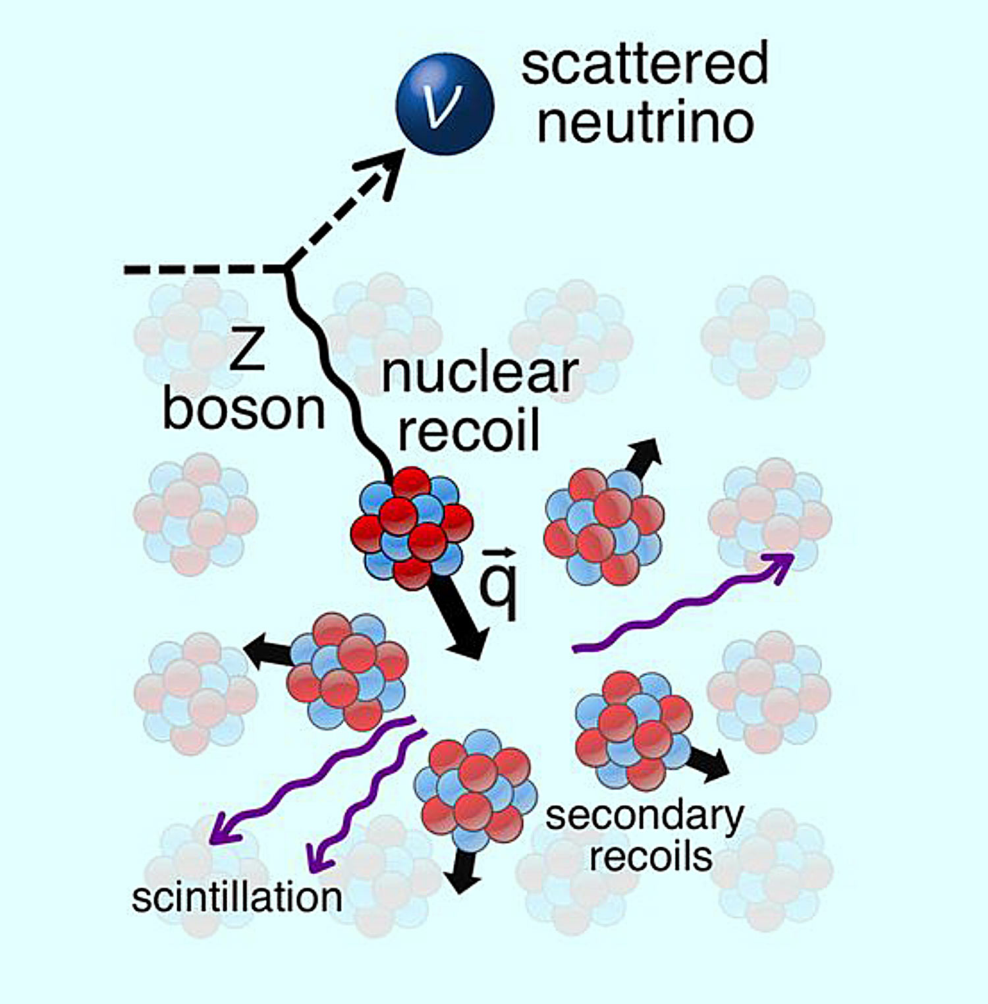
Precision CEvNS

Coherent elastic neutrino-nucleus scattering



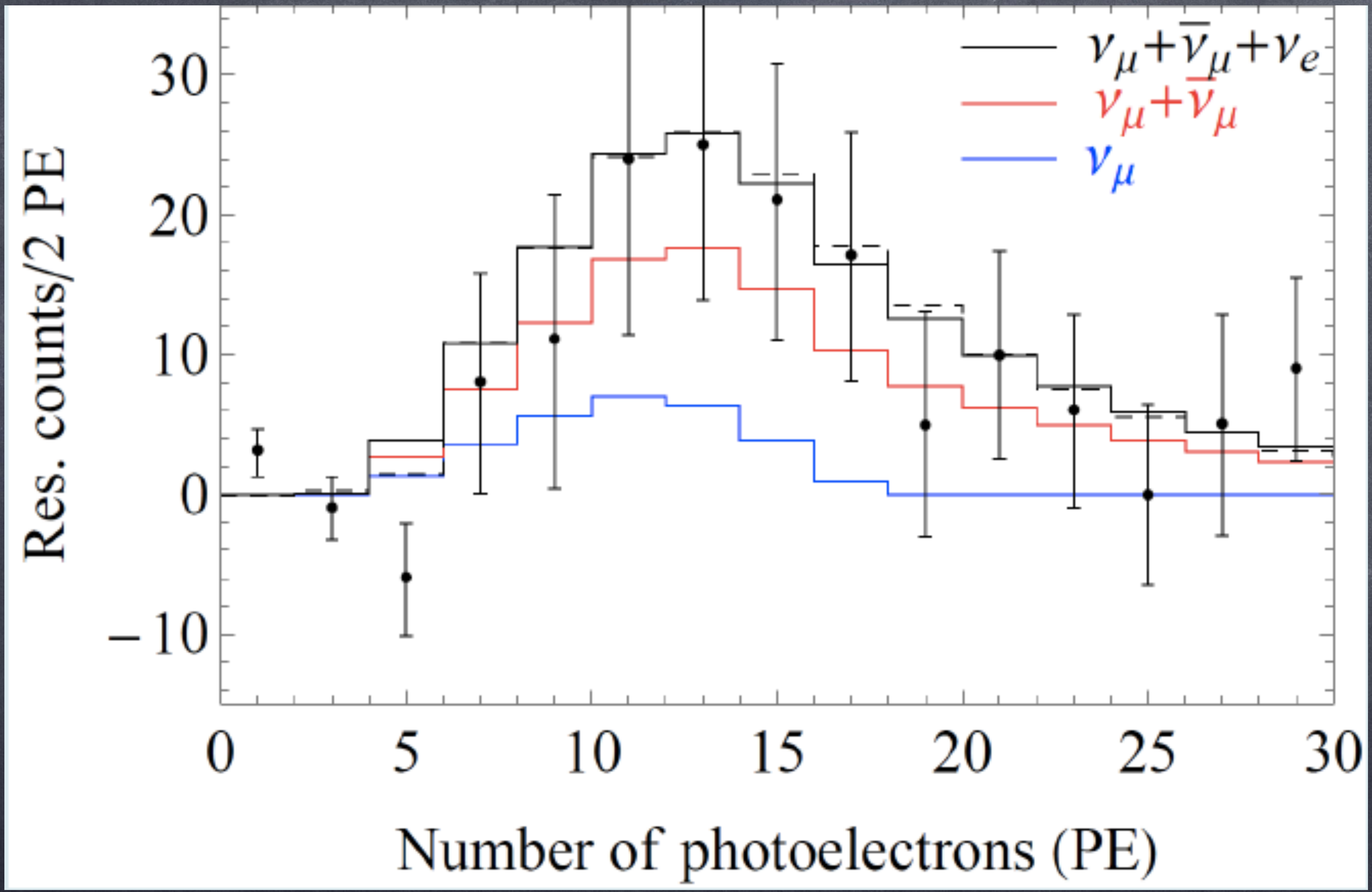
$$\frac{d\sigma}{dE_R} = \frac{G_F^2 M}{2\pi} Q_{\rm eff}^2 \left(2 - \frac{E_R M}{E_\nu^2}\right) F^2(q^2)$$

- Huge cross section but 1-10 keV nuclear recoil energy
- Sensitive only to spin-independent interactions

COHERENT

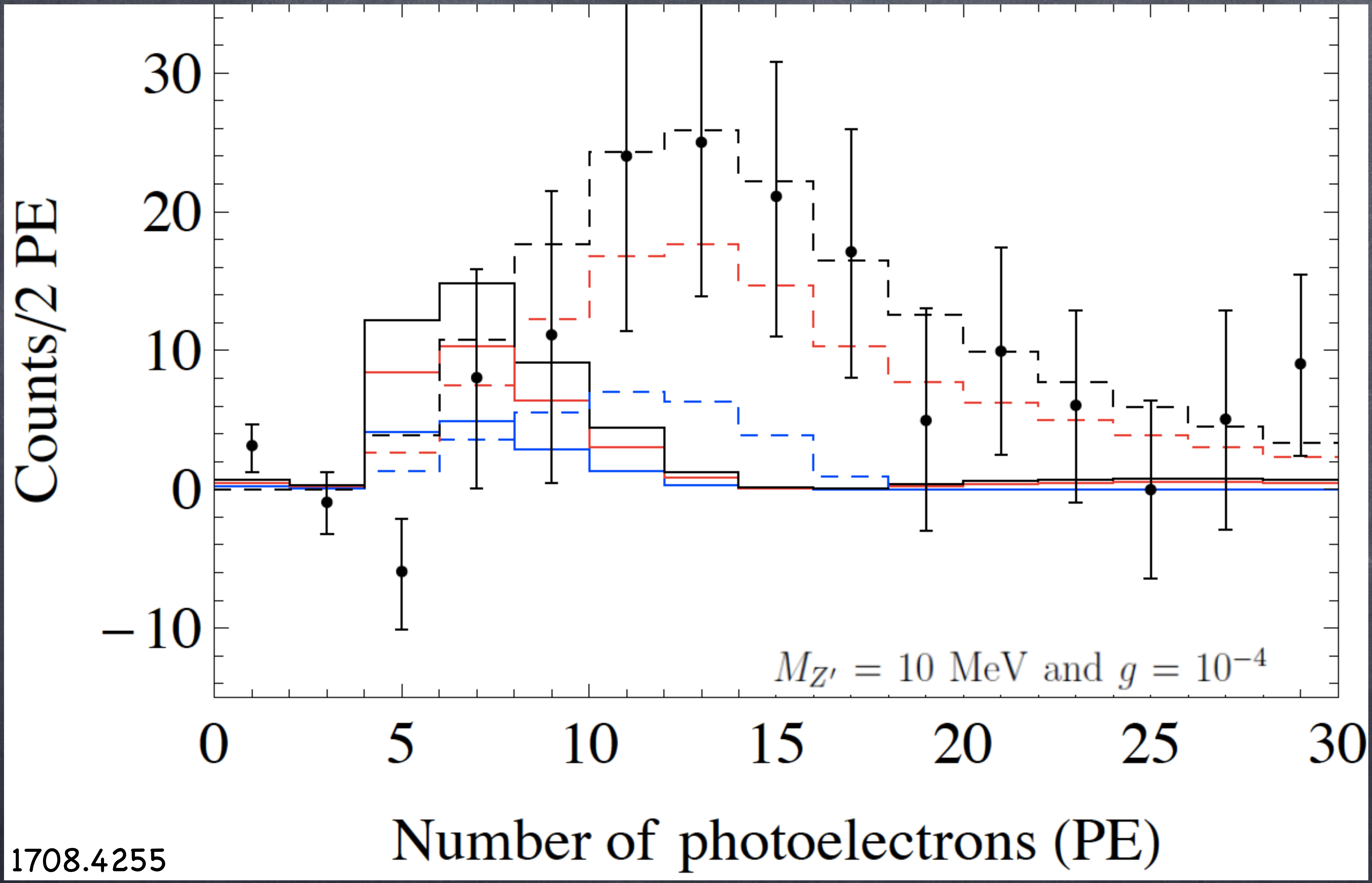
- Has seen CEvNS in 14.6 kg of CsI and 24.4 kg of Ar at 6.7 sigma and 3 sigma, respectively
- Data are consistent with SM
- Can probe NSI under contact approximation provided mediator is heavier than momentum transfer, 50 MeV

Standard Model spectrum



$$Q^2_{\mathrm{SM}} = \left(Z g_p^V + N g_n^V\right)^2 \qquad g_n^V = -\frac{1}{2} \simeq -10 g_p^V$$

Light vector mediator



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

Impact of quenching factor uncertainties

Quenching factor

Quenching factor is the ratio of the observable recoil energy in a nuclear recoil E_I to the observable recoil energy in an electron recoil of the same total recoil energy E_R:

$$Q \equiv E_I / E_R$$

Differential event rate

$$\frac{dR}{dE_I} = \frac{dR}{dE_R}\left(\frac{1}{Q} - \frac{E_I}{Q^2}\frac{dQ}{dE_I}\right)$$

where

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

Standard Lindhard model

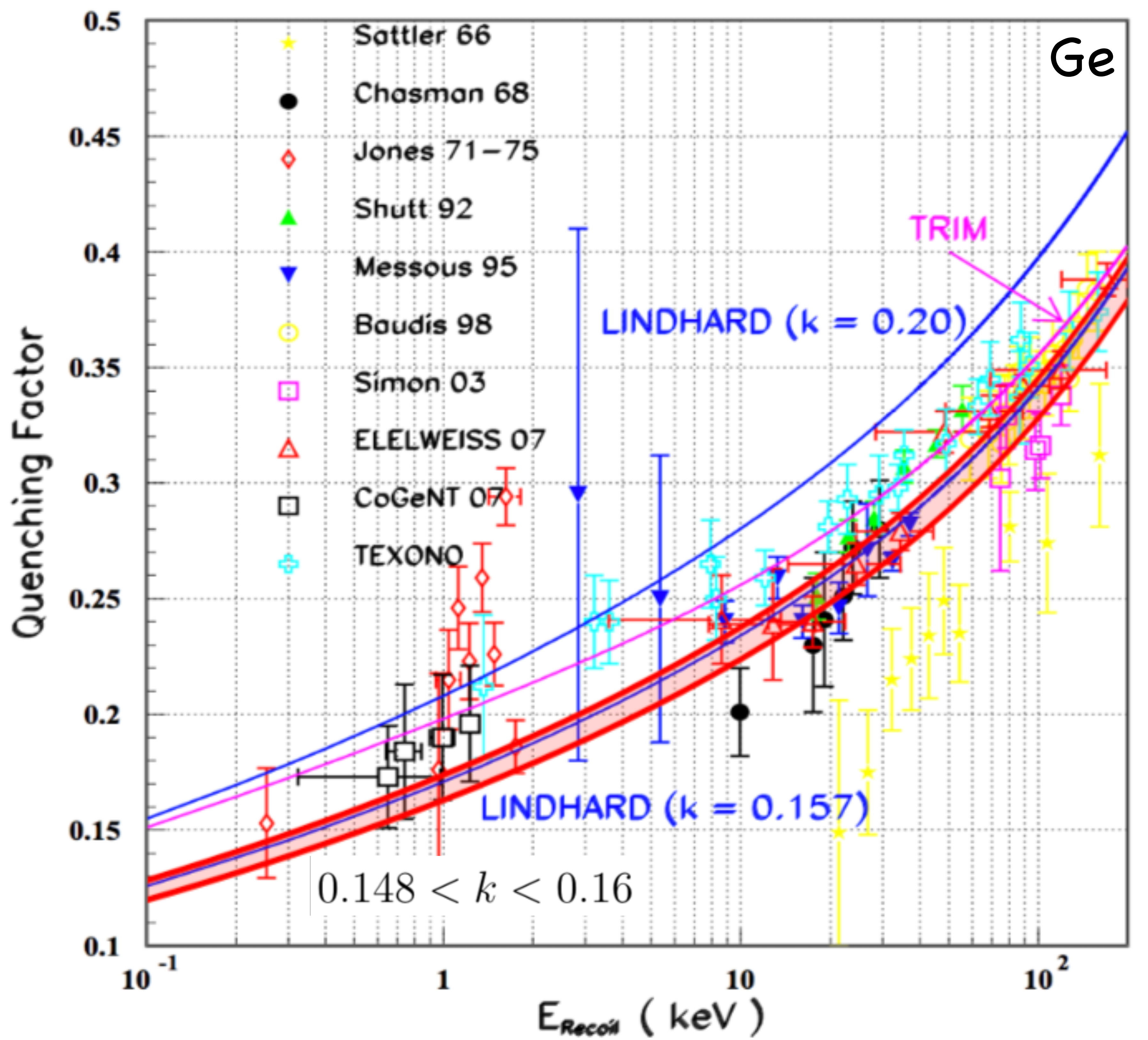
$$Q(E_R) = \frac{k\,g(\epsilon)}{1 + k\,g(\epsilon)}$$

$$k = 0.133 Z^{2/3} A^{-1/2}$$

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

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

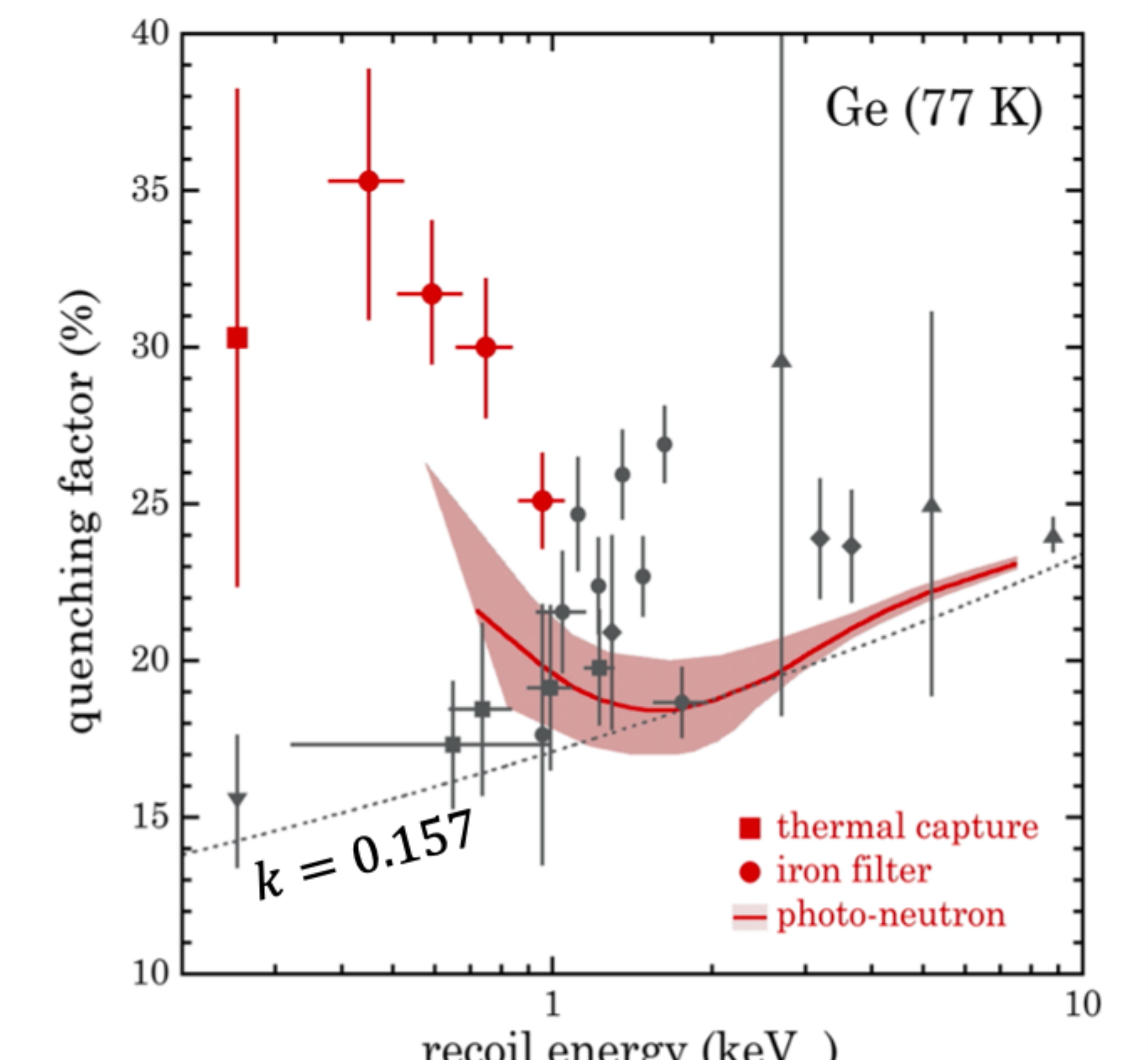
- Atomic binding energy of electrons is negligible
- Energy transfer to electrons is small relative to energy transfer to atom



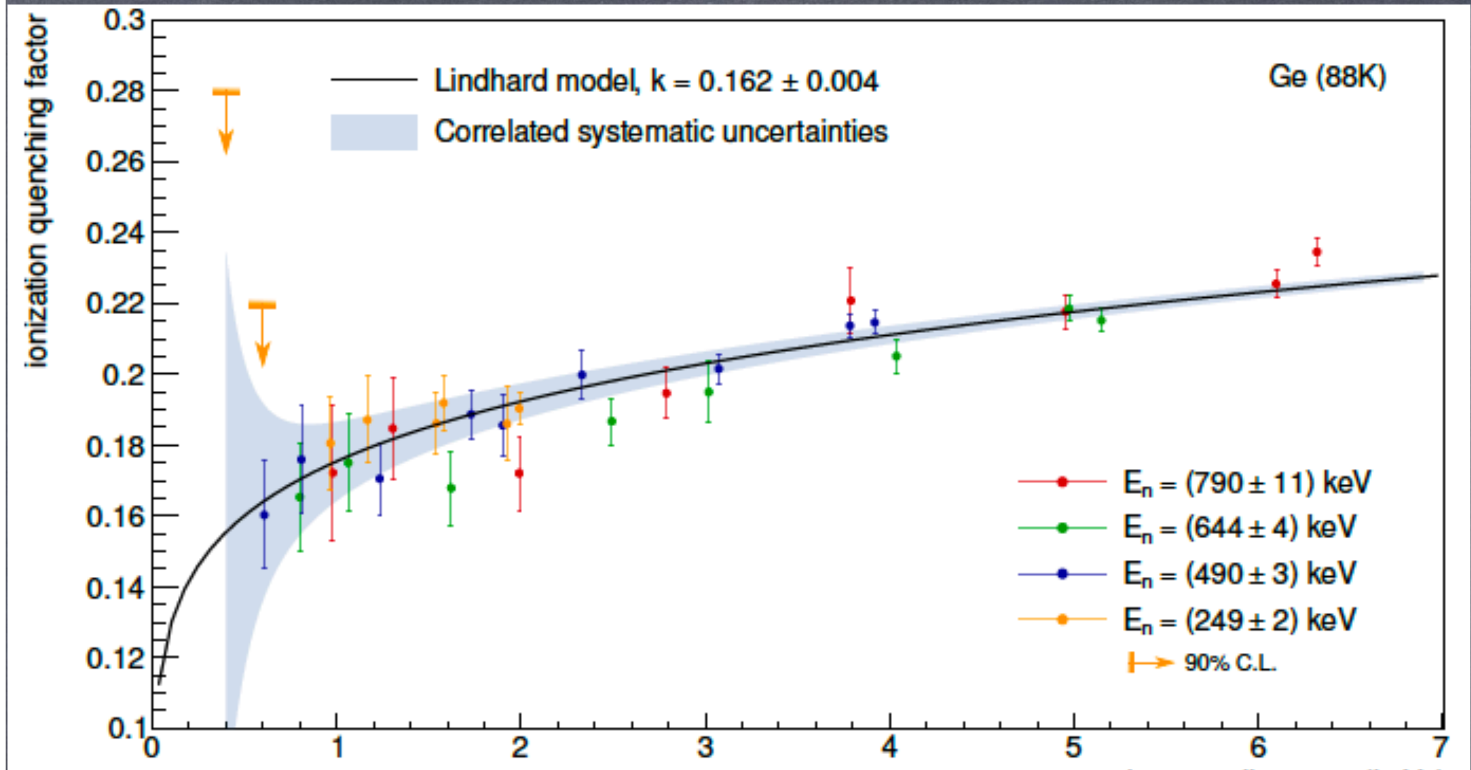
Ge
Sattler 66
Chasman 68
Jones 71−75
Shutt 92
Messous 95
Baudis 98
Simon 03
ELELWEISS 07
CoGeNT 07
TEXONO
TRIM
LINDHARD (k = 0.20)
LINDHARD (k = 0.157)
$0.148 < k < 0.16$
Quenching Factor
E_Recoil (keV)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
10^{-1}
1
10
10^{2}

0712.1645

Recent Ge QF measurements



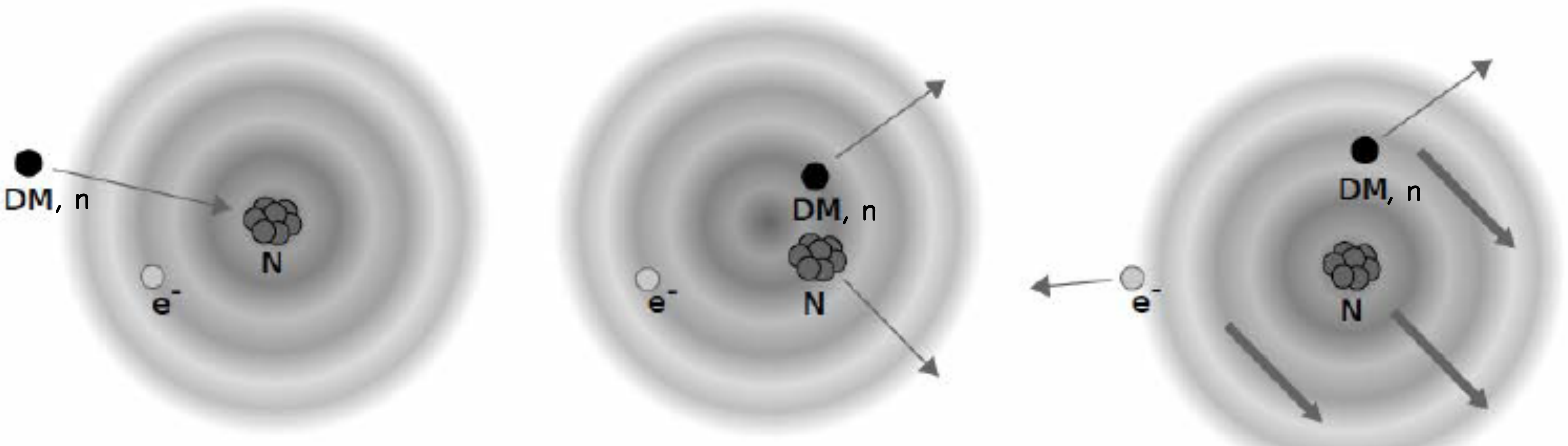
2102.10089



2202.03754

Migdal effect

... is the atomic ionization and excitation caused by the displacement between the atomic electrons and the instantaneously recoiling nucleus

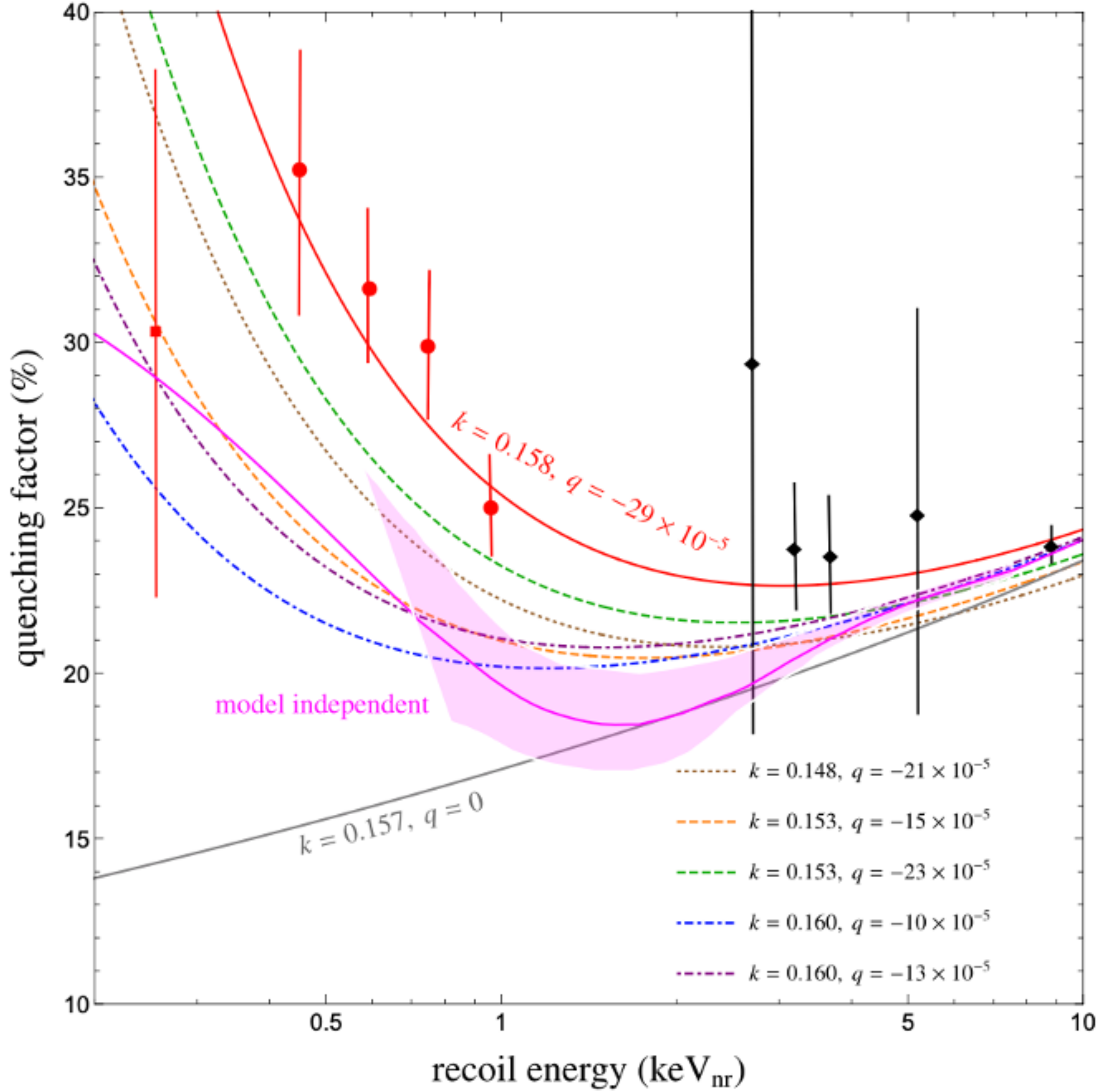


1711.09906

Modified Lindhard model

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

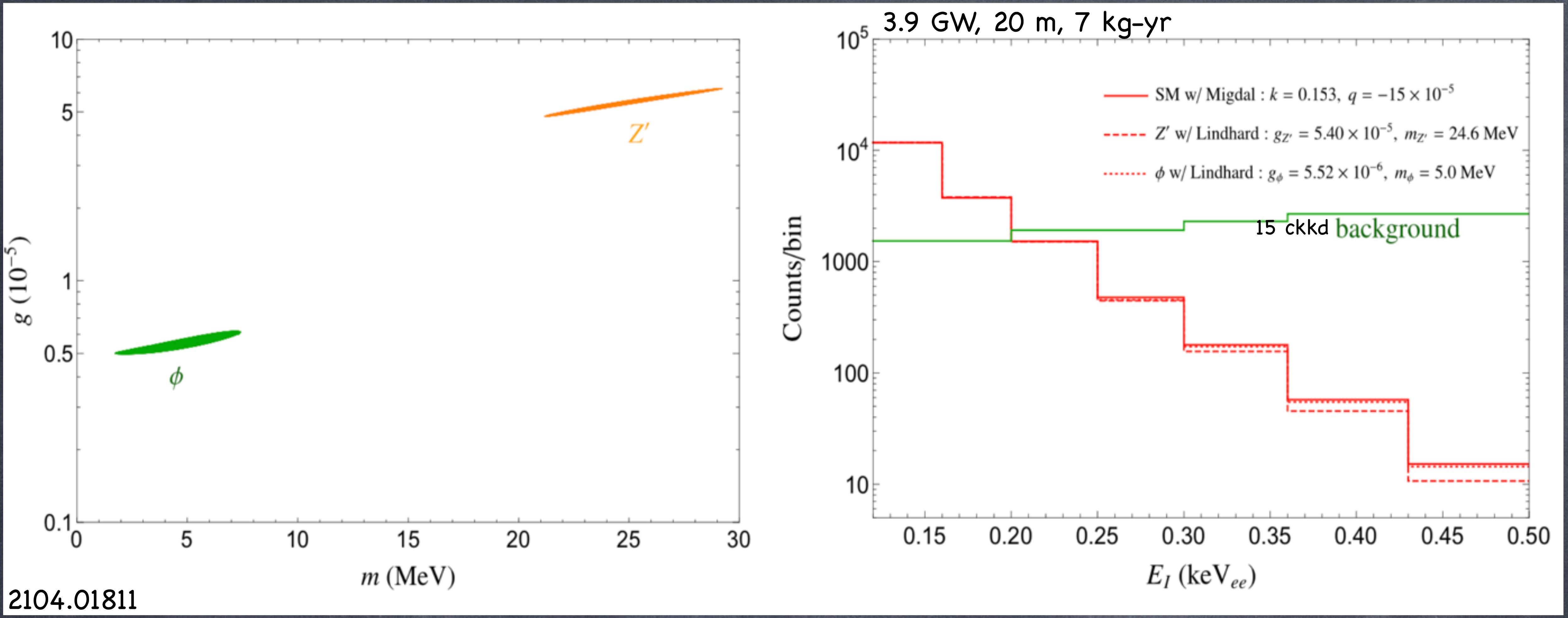
- Approaches standard Lindhard model at high recoil energies
- Atomic binding energy gives $q>0$ and explains an anticipated cutoff in Q at low recoil energies (1412.3028)
- Migdal effect modeled by $q<0$ gives an enhancement at low recoil energies (2104.01811)



quenching factor (%)
recoil energy (keV$_{nr}$)
40
35
30
25
20
15
10
0.5
1
5
10
$k = 0.158,\ q = -29 \times 10^{-5}$
model independent
$k = 0.157,\ q = 0$
$k = 0.148,\ q = -21 \times 10^{-5}$
$k = 0.153,\ q = -15 \times 10^{-5}$
$k = 0.153,\ q = -23 \times 10^{-5}$
$k = 0.160,\ q = -10 \times 10^{-5}$
$k = 0.160,\ q = -13 \times 10^{-5}$

2104.01811

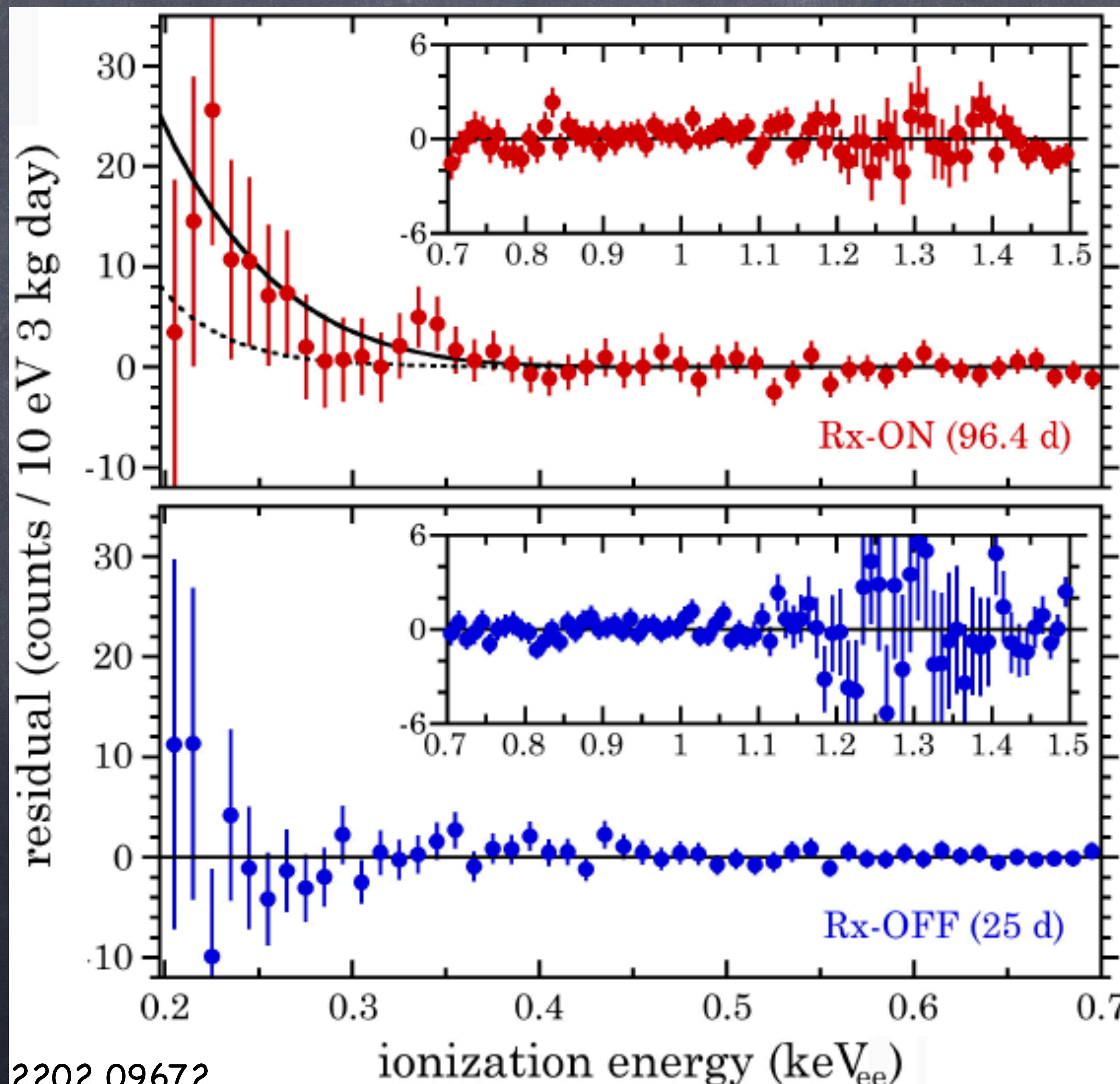
New physics



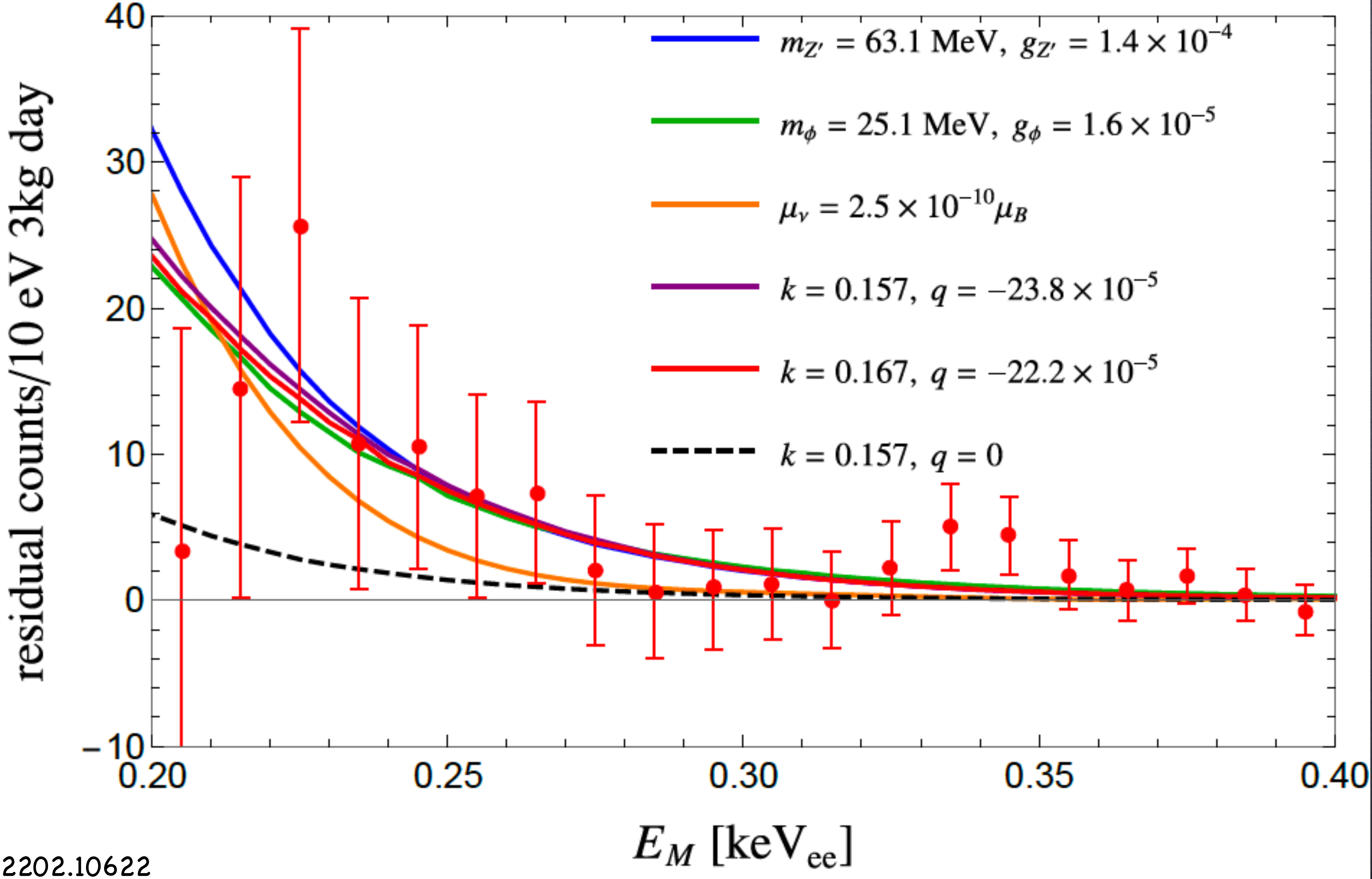
$m_{Z'}$/MeV	$g_{Z'} \times 10^5$	k	$q \times 10^5$	$\chi^2_{\min}$
16.2	4.24	0.148	−21	5.95
24.6	5.40	0.153	−15	1.32
32.1	6.71	0.160	−13	0.81
m_ϕ/MeV	$g_\phi \times 10^6$	k	$q \times 10^5$	$\chi^2_{\min}$
0.52	6.31	0.153	−23	2.11
5.0	5.52	0.153	−15	0.32
10.0	6.04	0.160	−10	1.46

First evidence with reactor neutrinos?

NCC-1701 is a 3 kg Ge detector placed 10 m from 2.96 GW Dresden-II power reactor

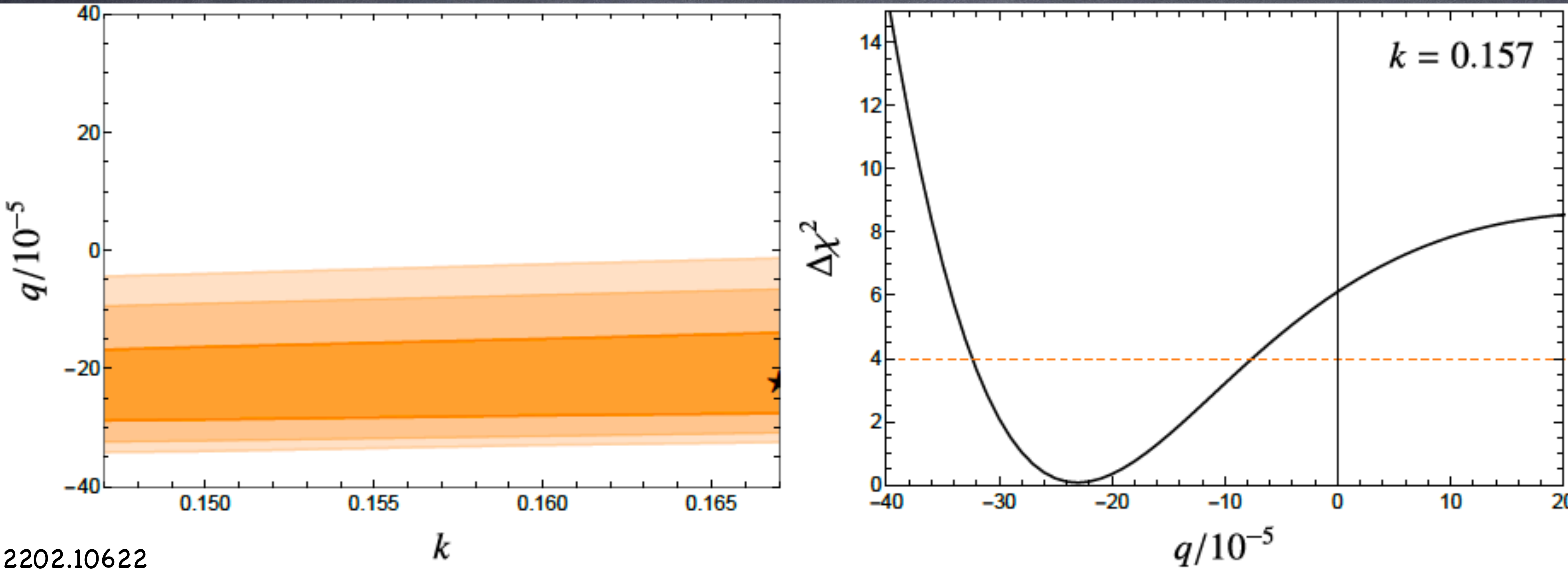


2202.09672



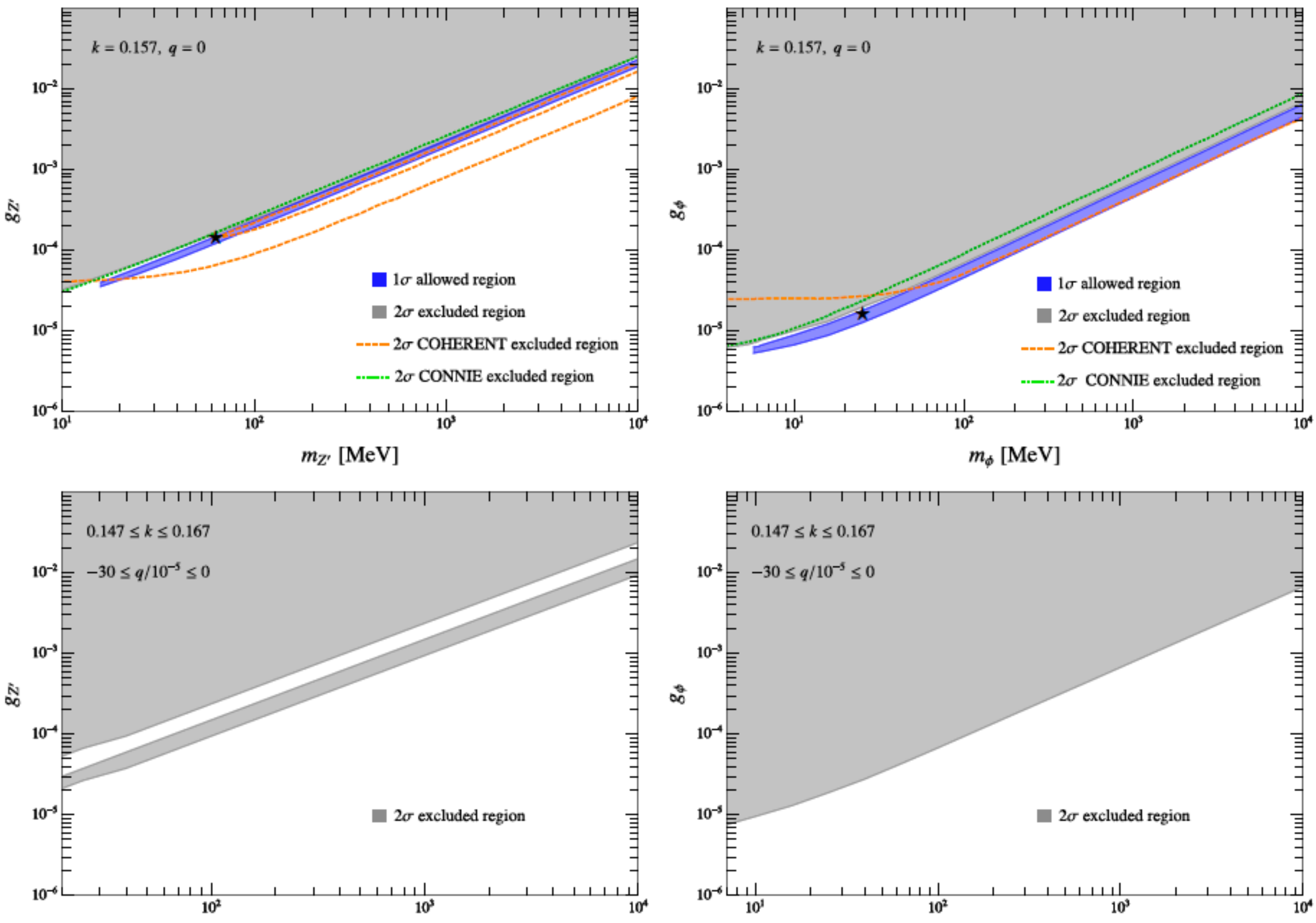
$m_{Z'}$ = 63.1 MeV, $g_{Z'}$ = 1.4 × 10^{-4}
m_ϕ = 25.1 MeV, g_ϕ = 1.6 × 10^{-5}
$\mu_\nu = 2.5 \times 10^{-10} \mu_B$
k = 0.157, q = −23.8 × 10^{-5}
k = 0.167, q = −22.2 × 10^{-5}
k = 0.157, q = 0
residual counts/10 eV 3kg day
E_M [keV_{ee}]
40
30
20
10
0
−10
0.20
0.25
0.30
0.35
0.40

2202.10622



40
20
0
−20
−40
$q/10^{-5}$
0.150
0.155
0.160
0.165
k
14
12
10
8
6
4
2
0
$\Delta\chi^2$
$k = 0.157$
−40
−30
−20
−10
0
10
20
$q/10^{-5}$

2202.10622


k = 0.157, q = 0
1σ allowed region
2σ excluded region
2σ COHERENT excluded region
2σ CONNIE excluded region
g_Z'
m_Z' [MeV]
g_φ
m_φ [MeV]
0.147 ≤ k ≤ 0.167
−30 ≤ q/10^−5 ≤ 0
10^−6
10^−5
10^−4
10^−3
10^−2
10^1
10^2
10^3
10^4

2202.10622

Impact of form factor uncertainties

Nuclear form factors

- Helm

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

- Symmeterized Fermi distribution

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

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

- Klein-Nystrand

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

Adopt same FF parameterizations for protons and neutrons

Rms radius of proton distributions known to one-per-mille

		Argon-18		Germanium-32				Xenon-54					
^{127}I	4.750	^{36}Ar (0.33%)	3.390	^{70}Ge (20.4%)	4.041	^{72}Ge (27.3%)	4.057	^{124}Xe (0.095%)	4.766	^{126}Xe (0.089%)	4.774	^{128}Xe (1.91%)	4.777
^{133}Cs	4.804	^{38}Ar (0.06%)	3.402	^{73}Ge (7.76%)	4.063	^{74}Ge (36.7%)	4.074	^{129}Xe (26.4%)	4.777	^{130}Xe (4.07%)	4.781	^{131}Xe (21.2%)	4.780
—	—	^{40}Ar (99.6%)	3.427	^{76}Ge (7.83%)	4.09	— —	—	^{132}Xe (26.9%)	4.785	^{134}Xe (10.4%)	4.789	^{136}Xe (8.86%)	4.796

- For protons, fix surface parameter and determine the other by fixing proton rms radius to exptl central value

- For neutrons, do the same except allow neutron rms radius to vary within r_p and r_p+0.3 fm for Cs, I, Ge, Xe since neutron skin of Pb is

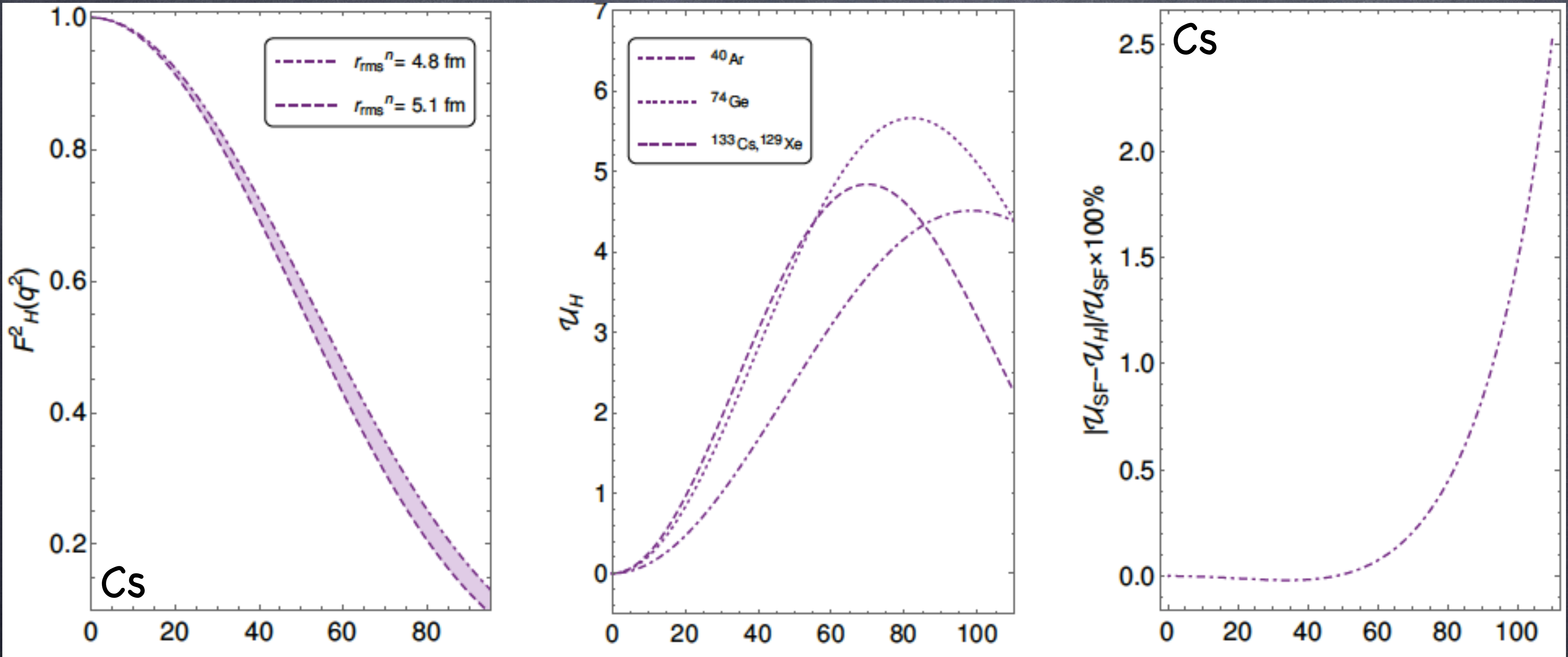
$$r^n_{\rm rms}(^{208}{\rm Pb}) - r^p_{\rm rms}(^{208}{\rm Pb}) = 0.283 \pm 0.071\ {\rm fm}$$

- ... and within r_p and either r_p+0.1 fm or r_p+0.2 fm for Ar since neutron skin of Ca is

$$r^n_{\rm rms}(^{48}{\rm Ca}) - r^p_{\rm rms}(^{48}{\rm Ca}) = 0.121 \pm 0.035\ {\rm fm}$$

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

+ 0.2 fm for Ar



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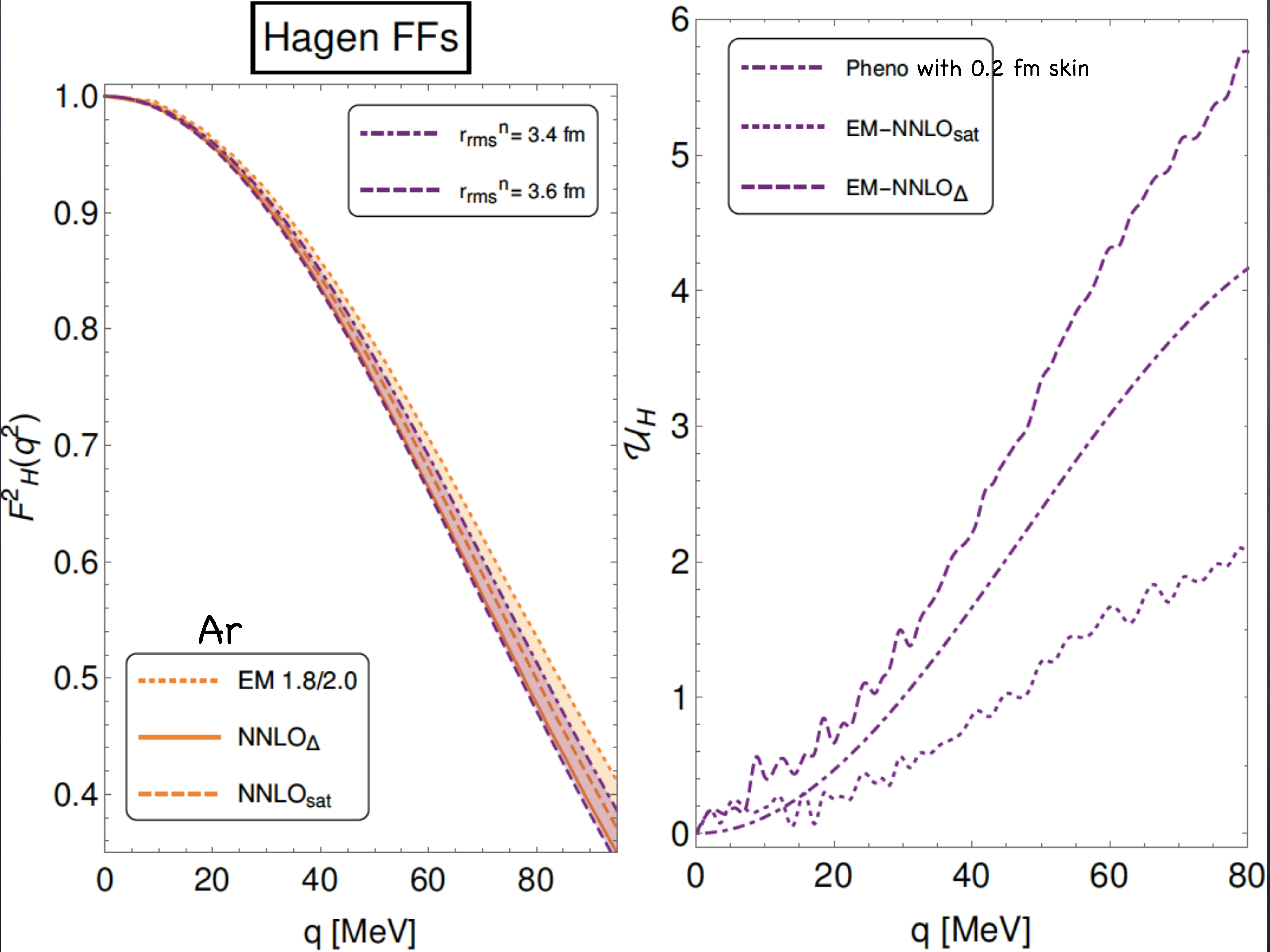
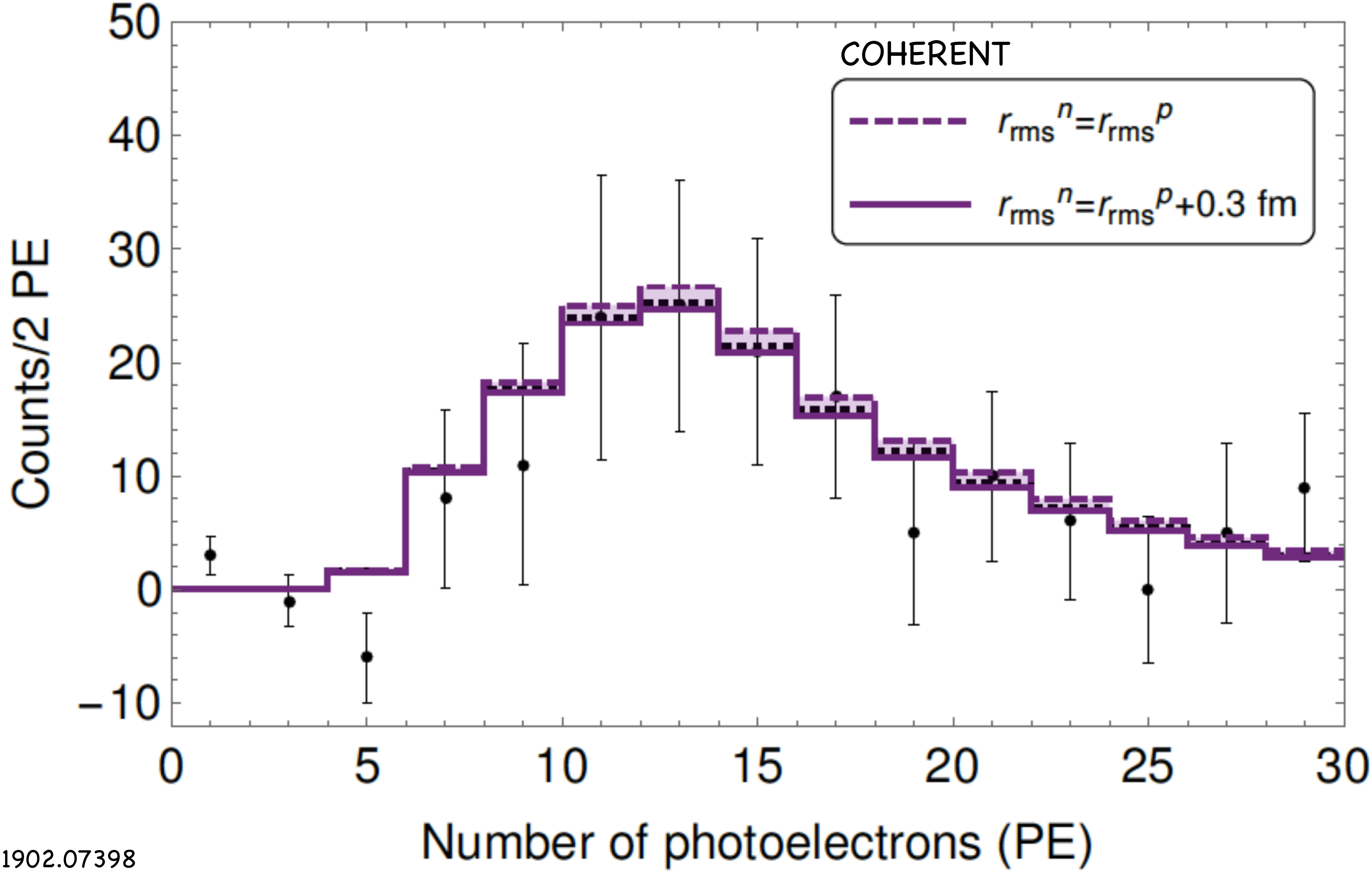
Size of the uncertainties do not depend on the FF chosen

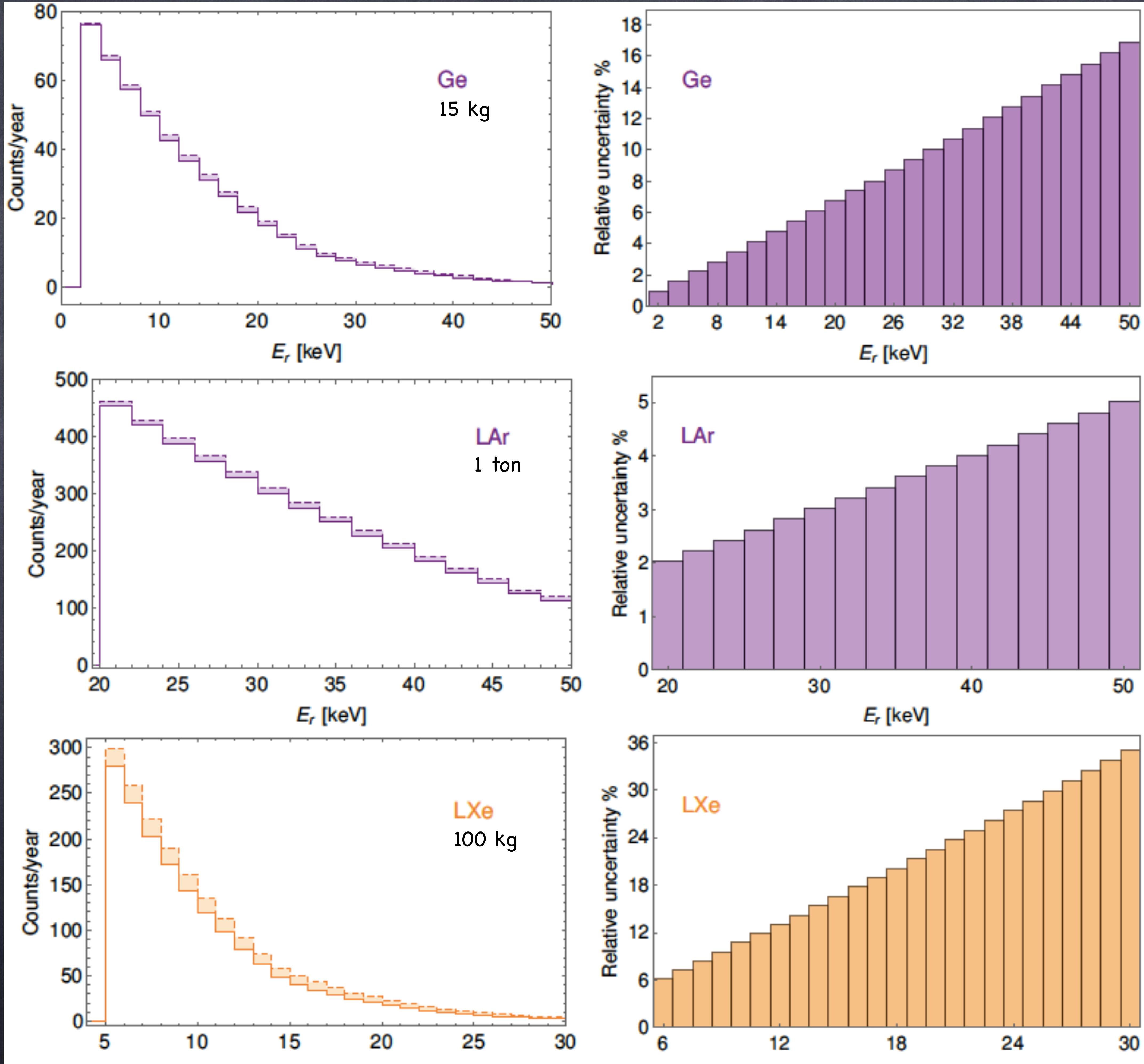


Hagen FFs
$r_{rms}{}^n$= 3.4 fm
$r_{rms}{}^n$= 3.6 fm
Ar
EM 1.8/2.0
$NNLO_\Delta$
$NNLO_{sat}$
$F^2_H(q^2)$
q [MeV]
Pheno with 0.2 fm skin
EM−$NNLO_{sat}$
EM−$NNLO_\Delta$
$\mathcal{U}_H$
q [MeV]



COHERENT
$r_{rms}{}^n = r_{rms}{}^p$
$r_{rms}{}^n = r_{rms}{}^p + 0.3$ fm
Counts/2 PE
Number of photoelectrons (PE)

1902.07398


Ge
15 kg
Counts/year
E_r [keV]
Ge
Relative uncertainty %
E_r [keV]
LAr
1 ton
Counts/year
E_r [keV]
LAr
Relative uncertainty %
E_r [keV]
LXe
100 kg
Counts/year
E_r [keV]
LXe
Relative uncertainty %
E_r [keV]

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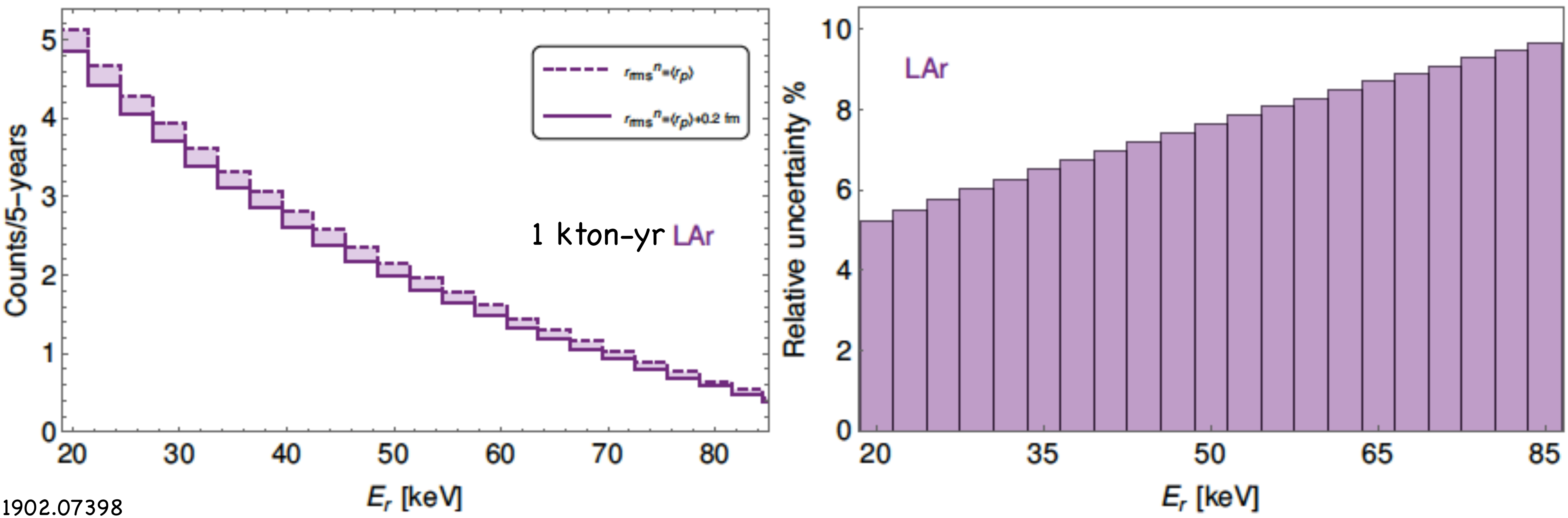
Backgrounds to dark matter searches



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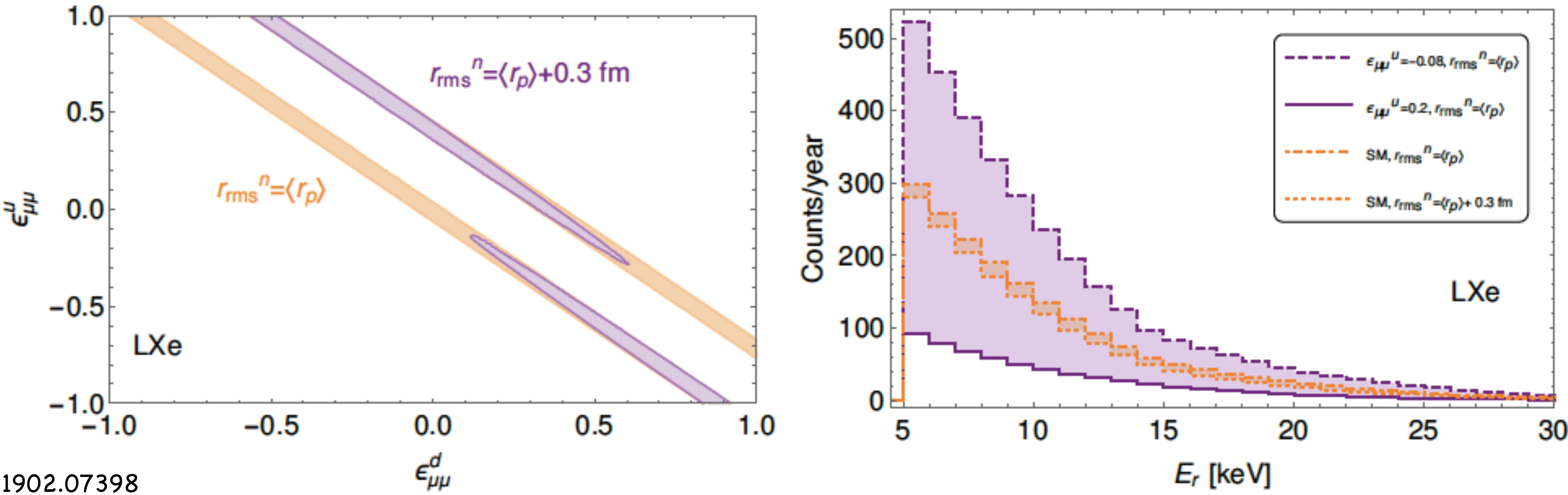
NSI



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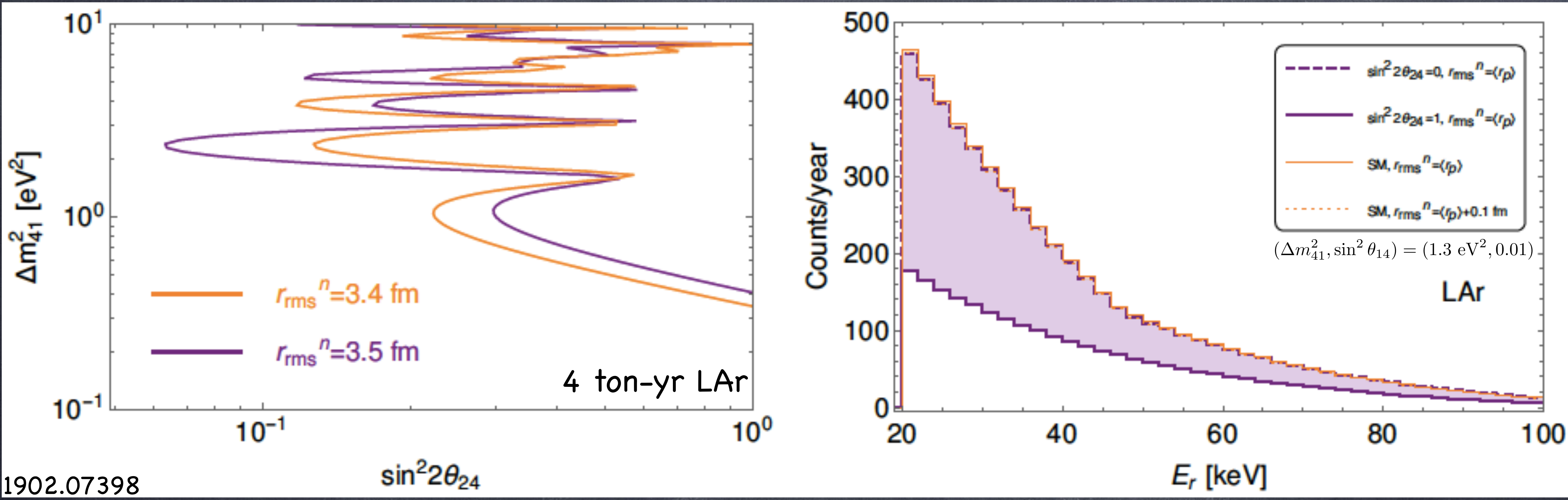
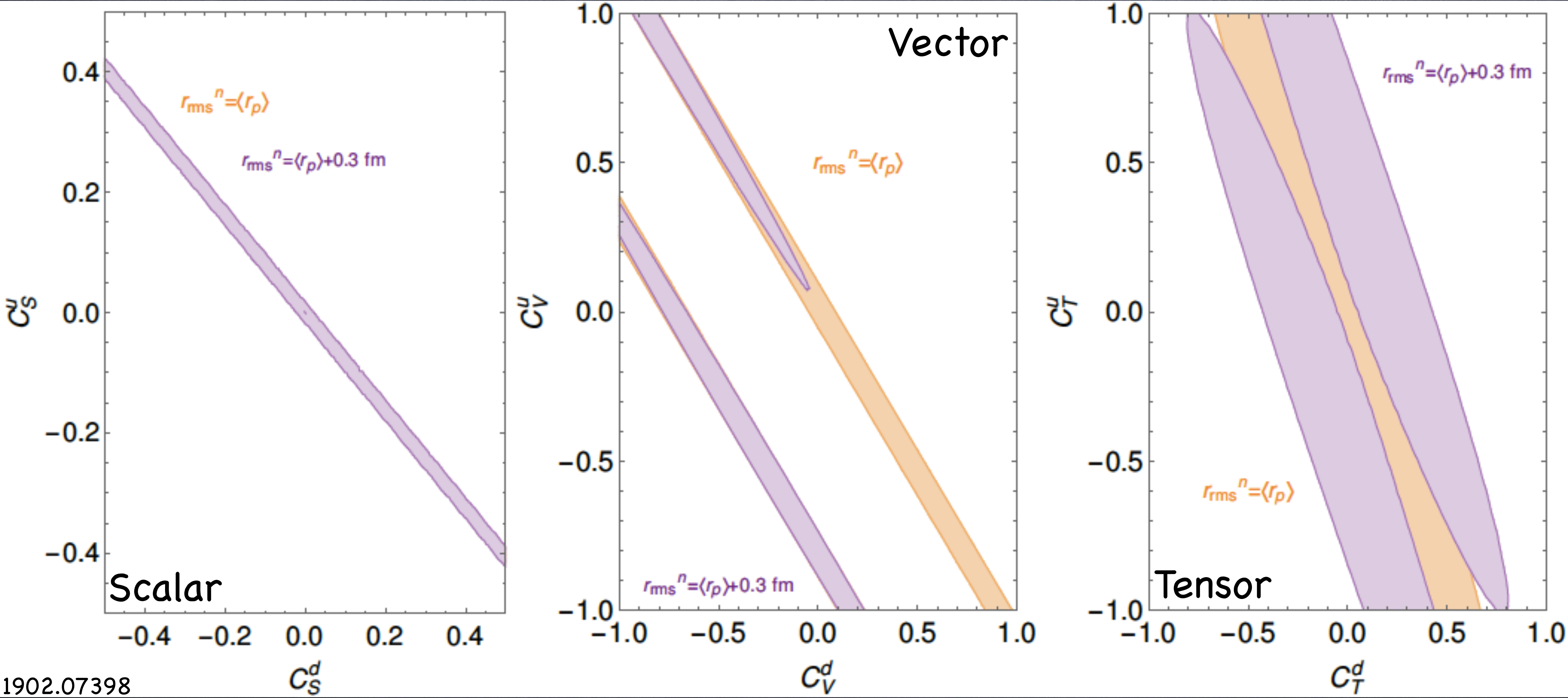
3+1 sterile neutrino oscillations



A 3% change in r_n has a big effect on the exclusion

Neutrino generalized interactions

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



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Summary

- Recent measurements of Ge QF depart from standard Linhard model
- May be caused by Migdal effect, which can be parametrized by $q<0$ in modified Lindhard model
- SM with given set of Migdal parameters can be simultaneously degenerate with Z′ and scalar mediators
- Recent evidence for CEvNS of reactor neutrinos provides independent preference for $q<0$ at 2 sigma
- New physics constraints quite sensitive to QF at low recoil energies

- FF uncertainties are relevant for momentum transfers above 20 MeV, so not important for CEvNS induced by reactor and solar neutrinos

- FF uncertainties are independent of the parameterization chosen

- New physics searches strongly impacted by FF uncertainties