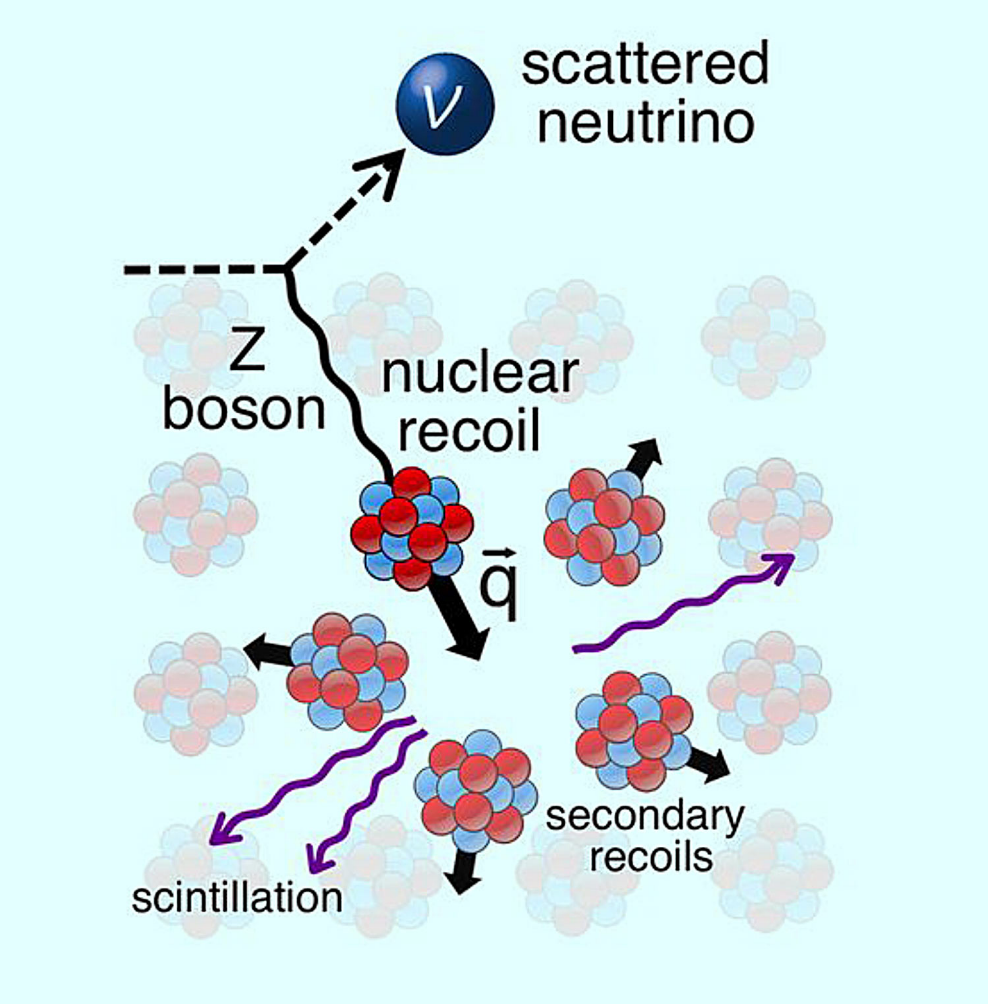
Precision CEvNS

Coherent elastic neutrino-nucleus scattering



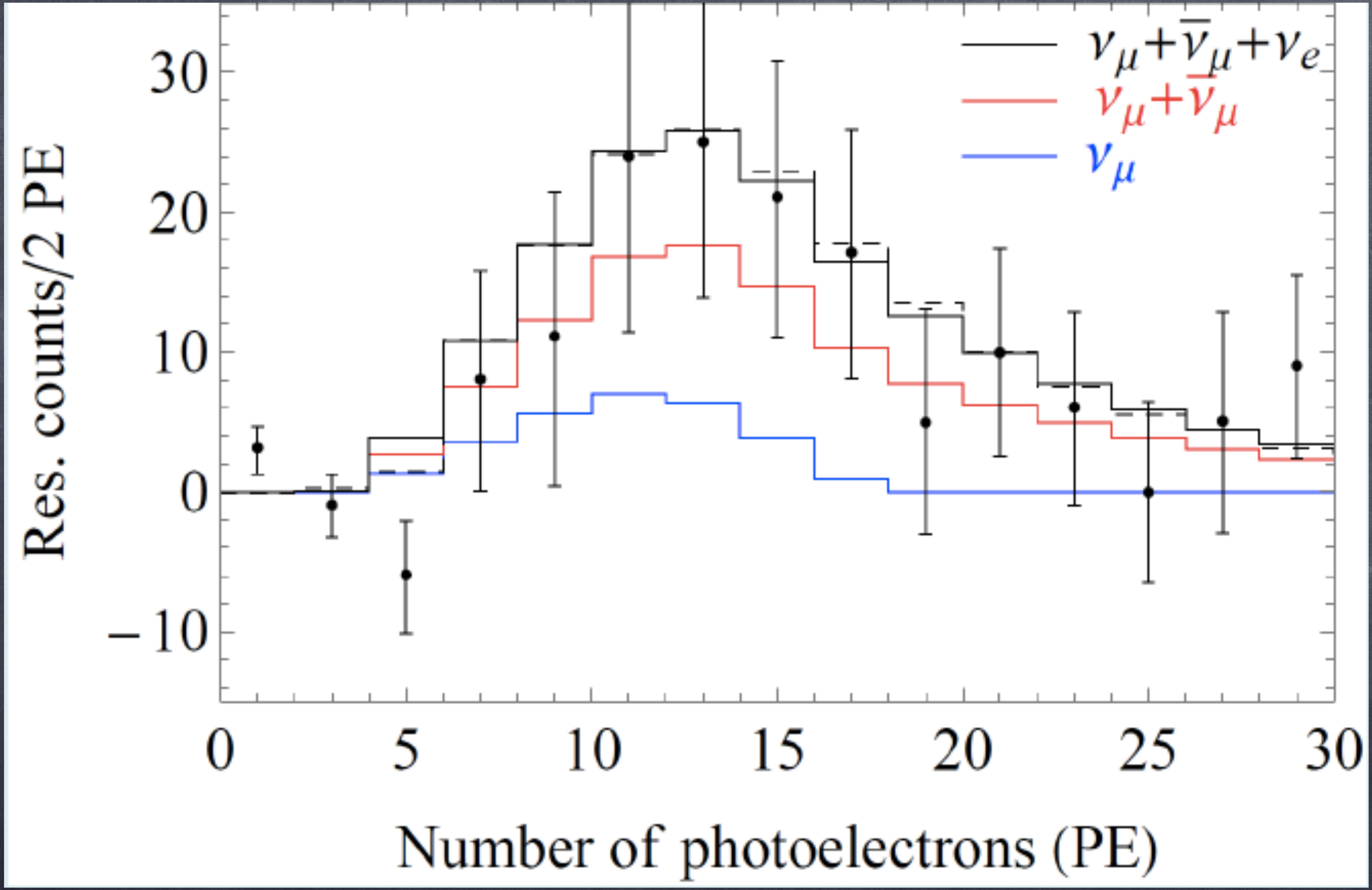
$$\frac{d\sigma}{dE_R} = \frac{G_F^2 M}{2\pi} Q^2 \left(2 - \frac{E_R M}{E_\nu^2}\right) F^2(q^2)$$

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

COHERENT

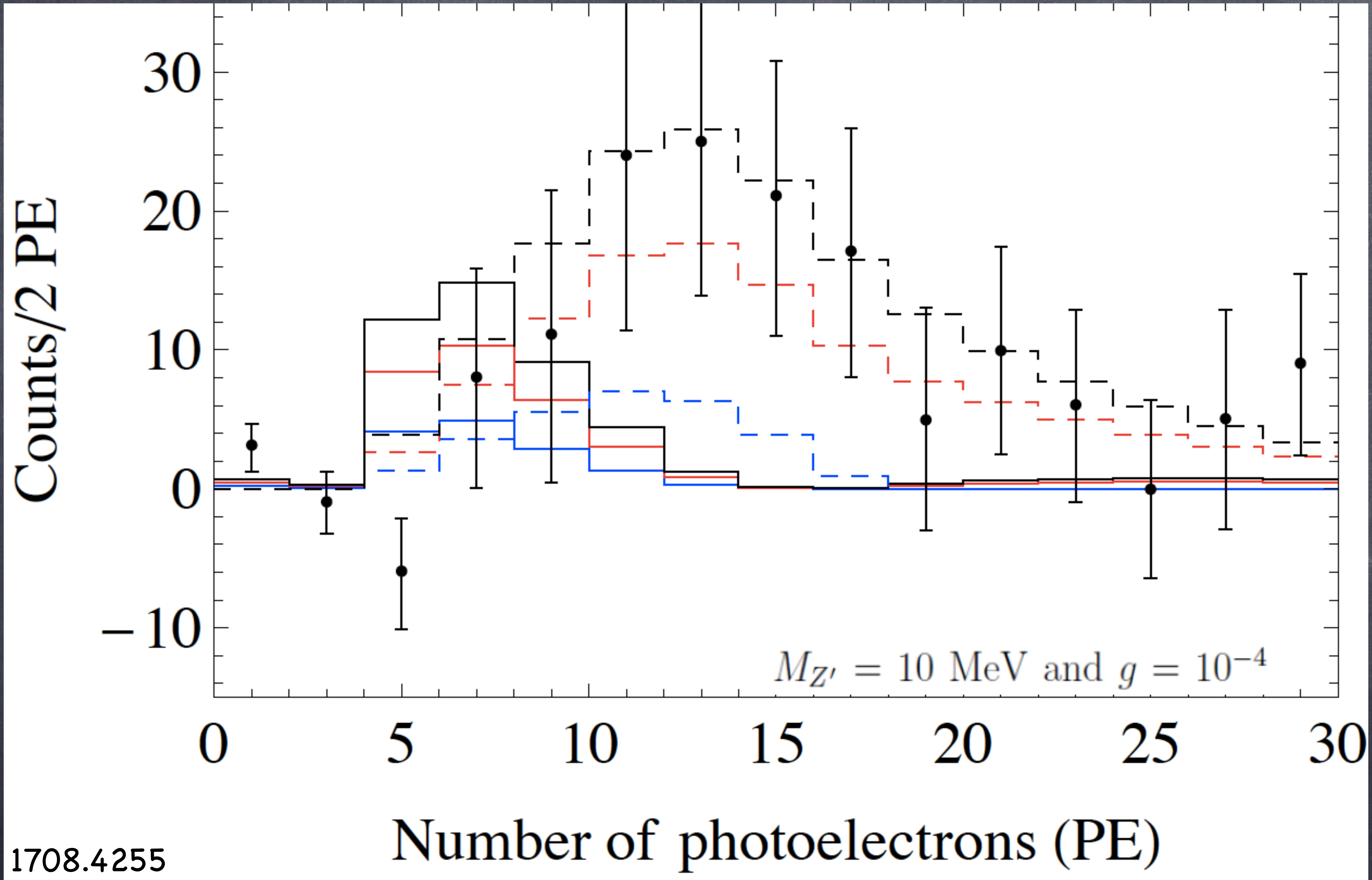
- Has seen CEvNS in 14.6 kg of CsI and 24.4 kg of Ar at 6.7 sigma and 3 sigma, respectively
- Data are consistent with SM
- Can probe NSI under contact approximation provided mediator is heavier than momentum transfer, 50 MeV

Standard Model spectrum



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

Light vector mediator



1708.4255

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

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

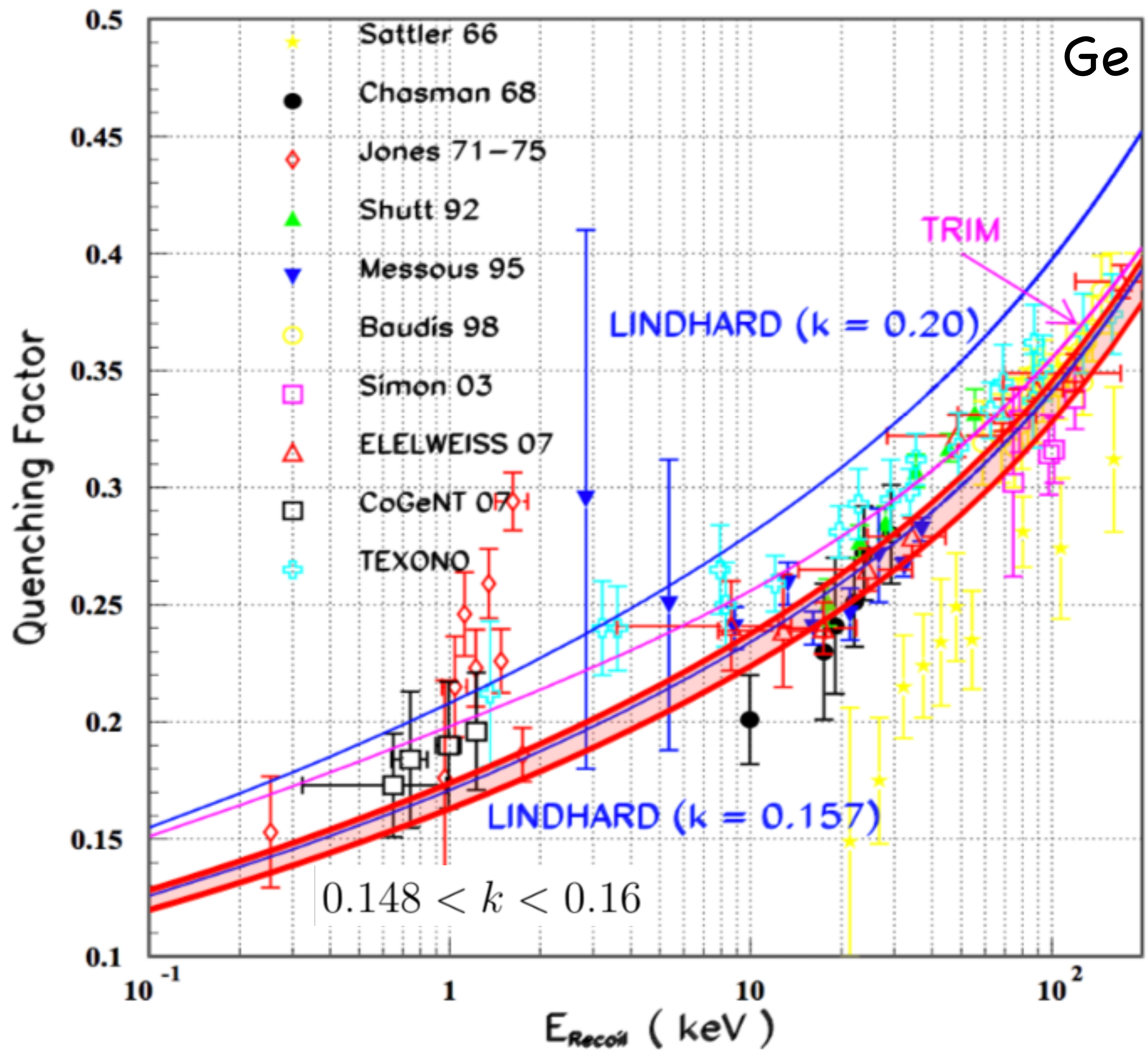
$$Q(E_R) = \frac{k\, g(\epsilon)}{1 + k\, g(\epsilon)}$$

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

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

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

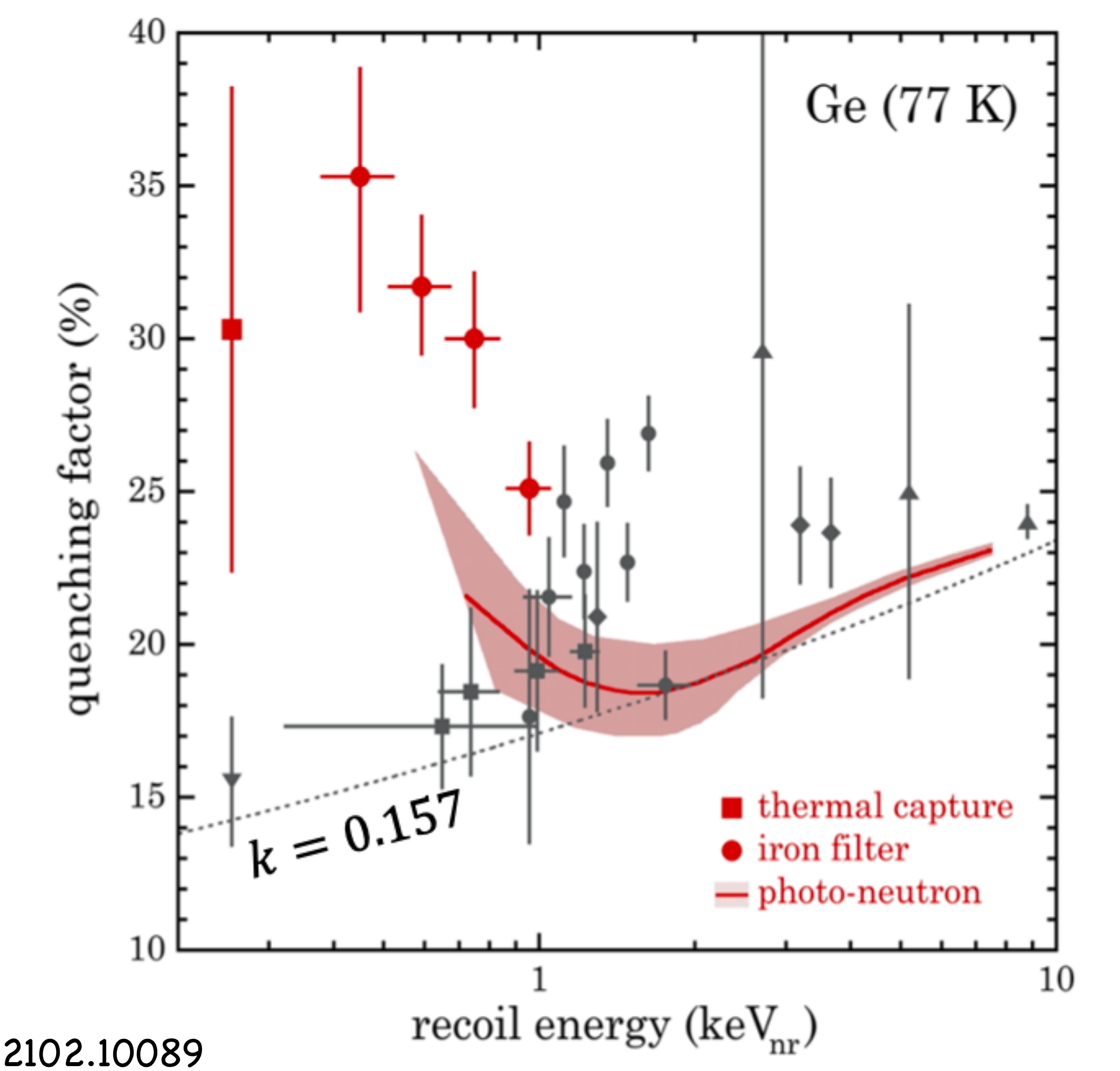
- Atomic binding energy of electrons is negligible
- Energy transfer to electrons is small relative to energy transfer to atom



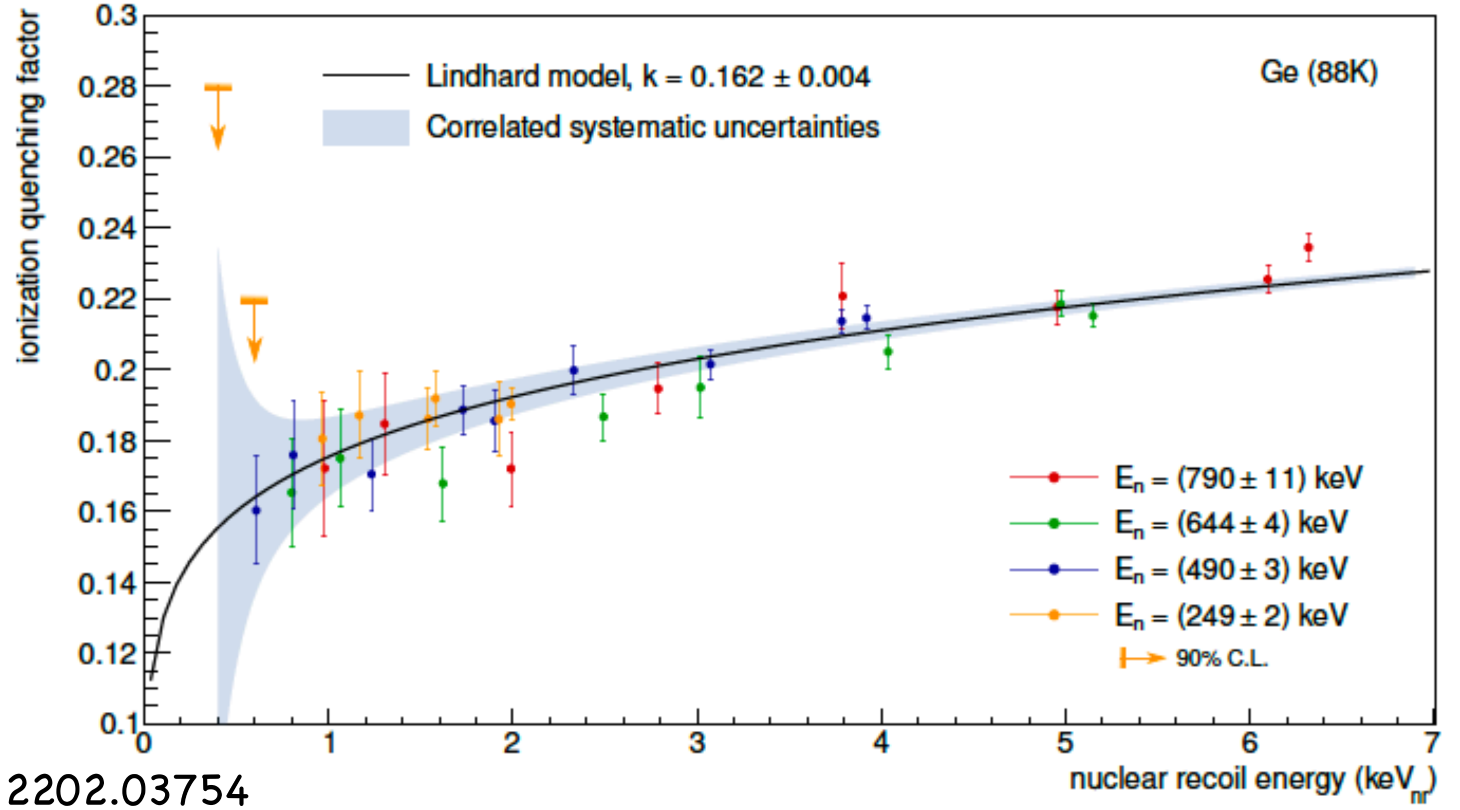
$0.148 < k < 0.16$

0712.1645

Recent Ge QF measurements



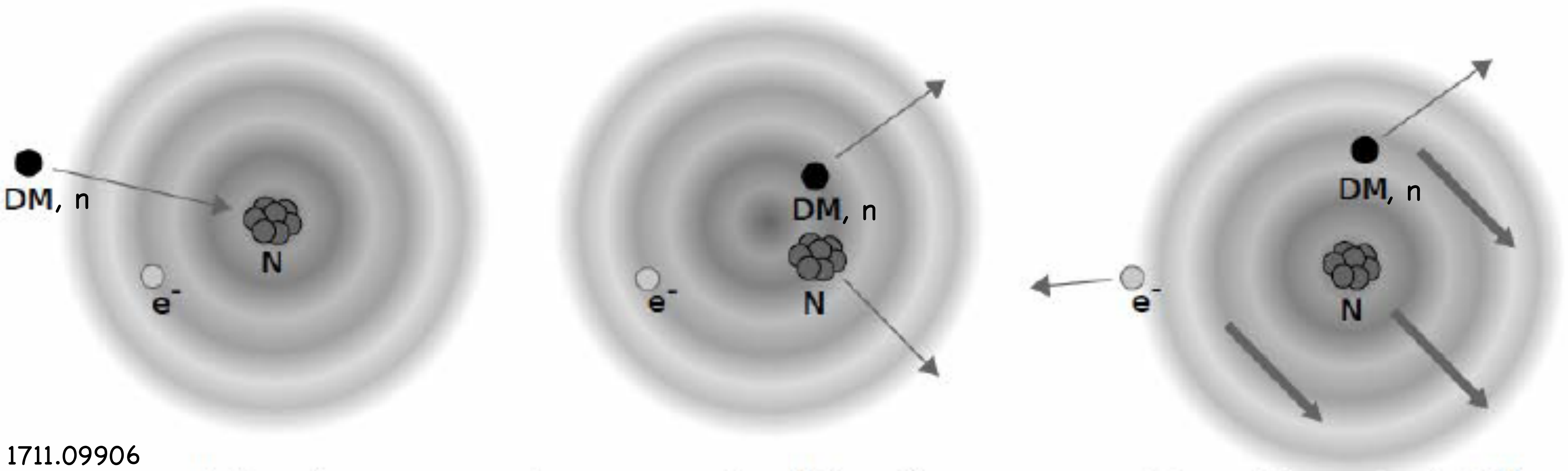
2102.10089



2202.03754

Migdal effect

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

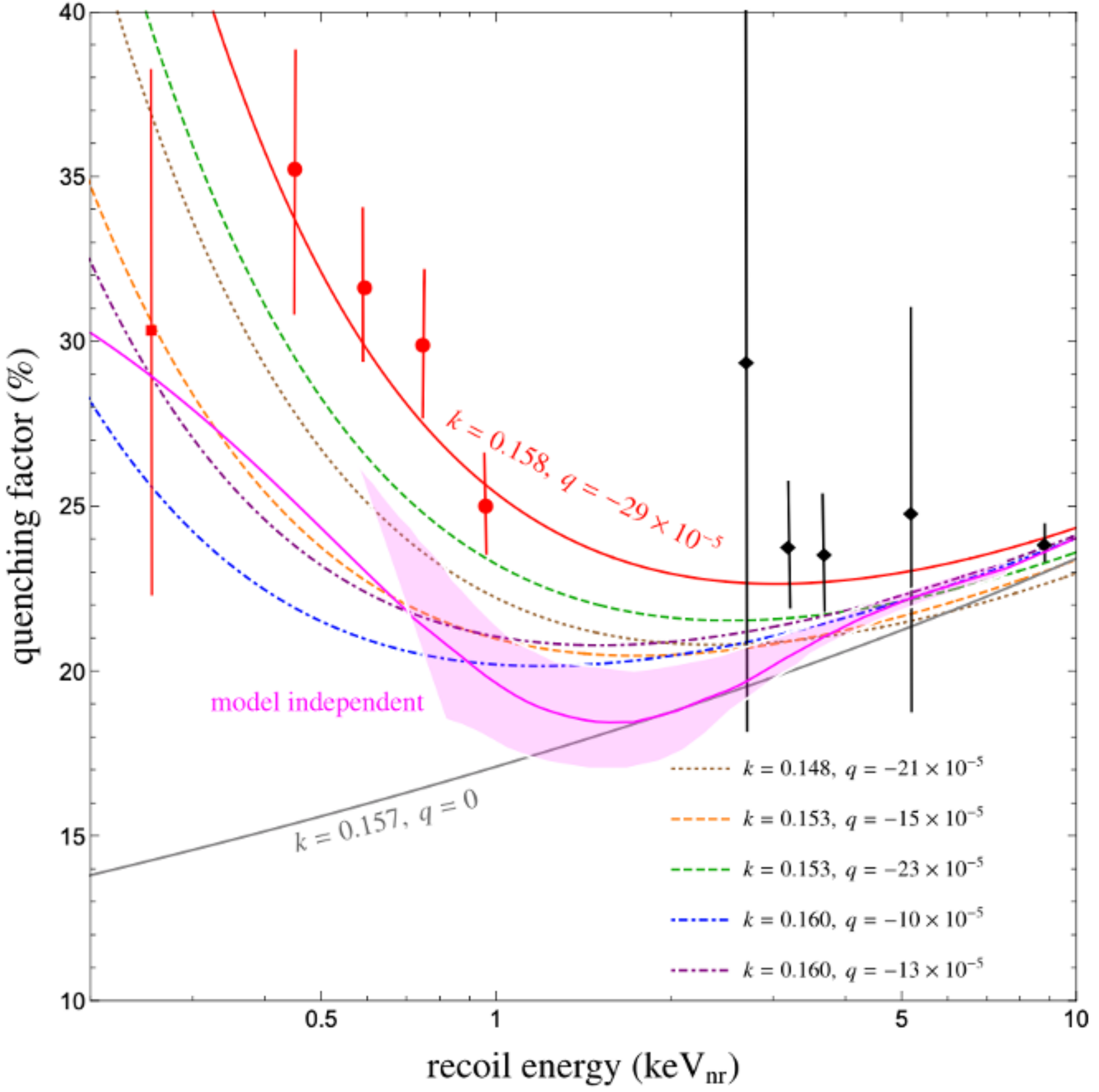


1711.09906

Modified Lindhard model

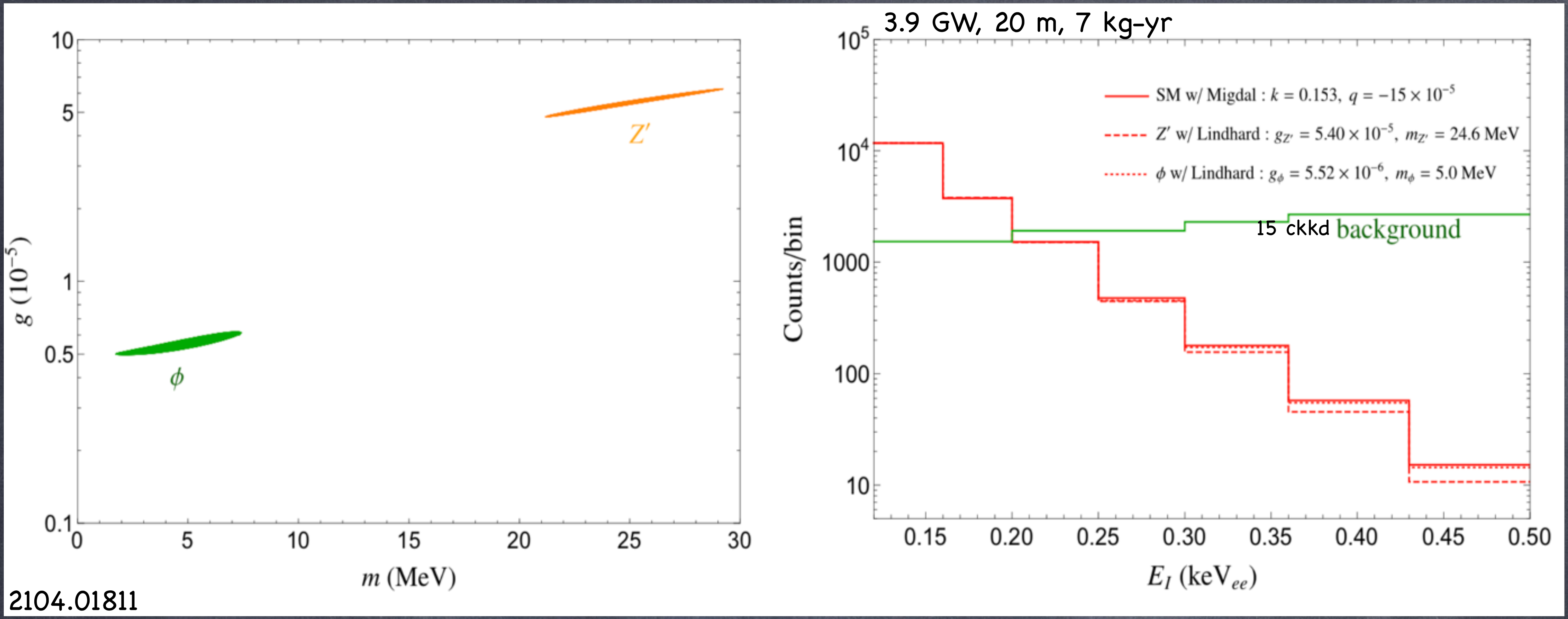
$$Q(E_R) = \frac{k\,g(\epsilon)}{1 + k\,g(\epsilon)} \enclose{circle}{- \frac{q}{\epsilon}}$$

- 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)


40
35
30
25
20
15
10
quenching factor (%)
0.5
1
5
10
recoil energy (keV$_{nr}$)
$k = 0.158,\ q = -29 \times 10^{-5}$
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



3.9 GW, 20 m, 7 kg-yr

15 ckkd

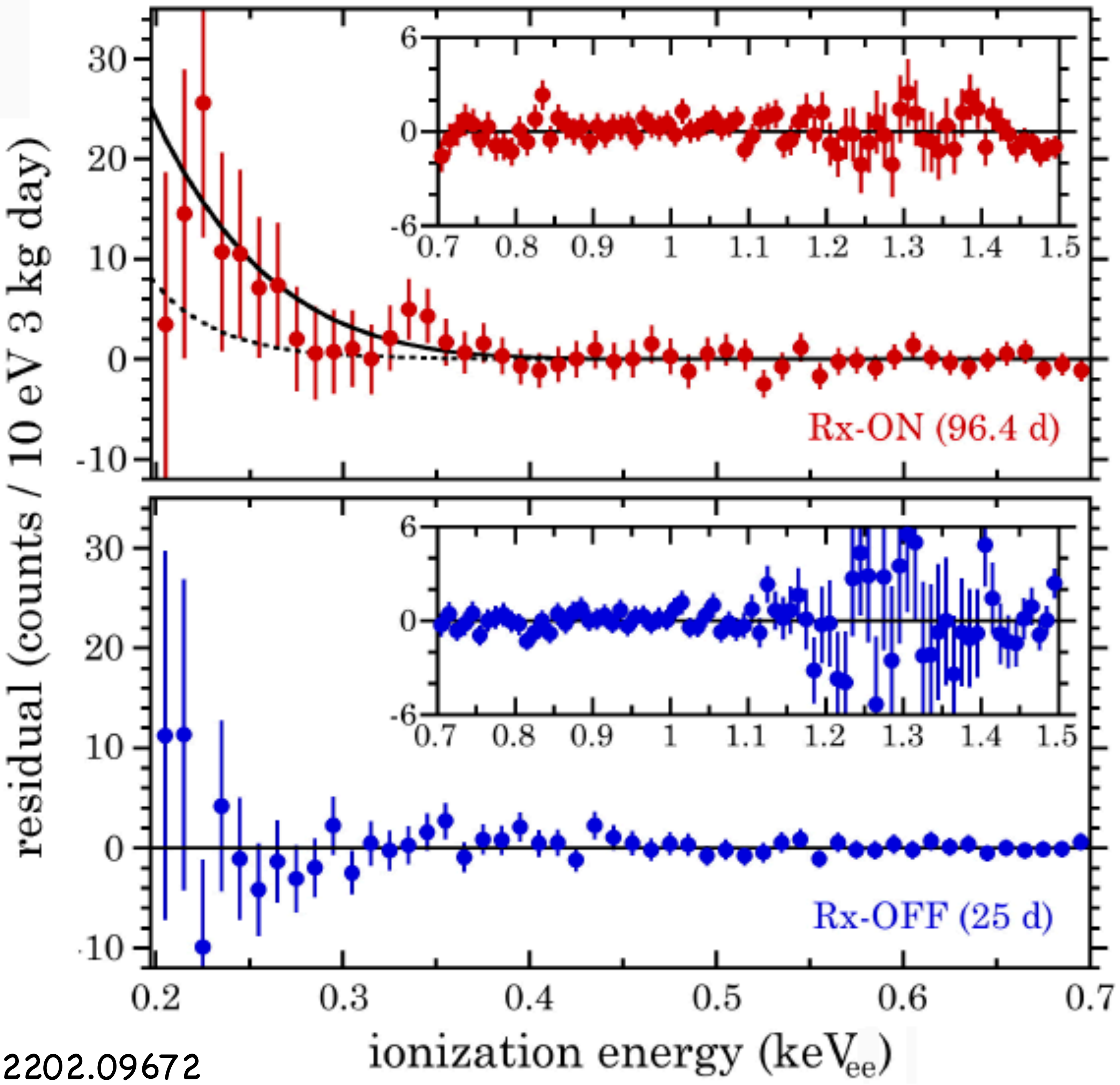
2104.01811

$m_{Z'}/\mathrm{MeV}$	$g_{Z'} \times 10^5$	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

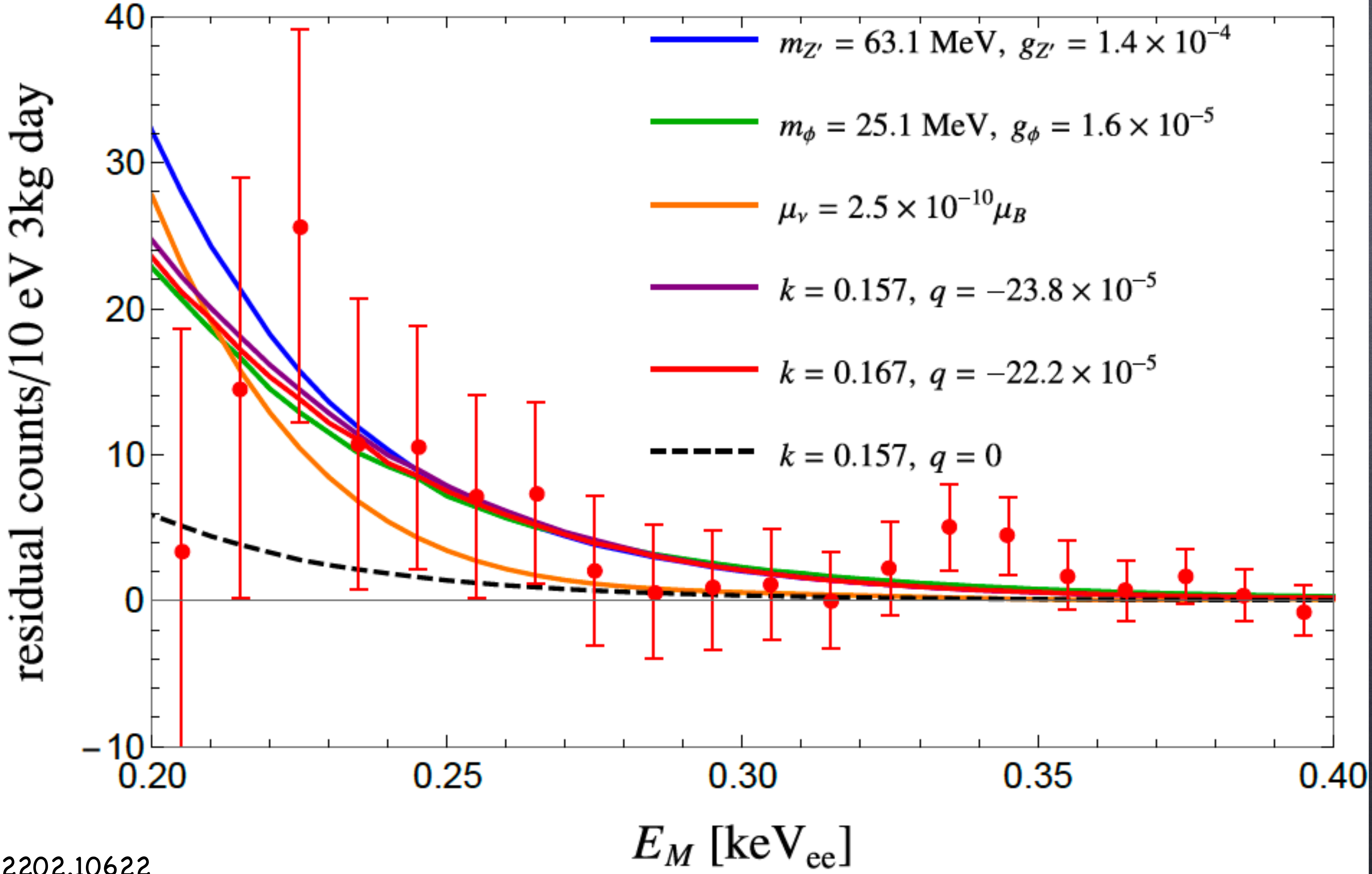
m_ϕ/MeV	$g_\phi \times 10^6$	k	$q \times 10^5$	χ^2_{min}
0.52	6.31	0.153	−23	2.11
5.0	5.52	0.153	−15	0.32
10.0	6.04	0.160	−10	1.46

First evidence with reactor neutrinos?

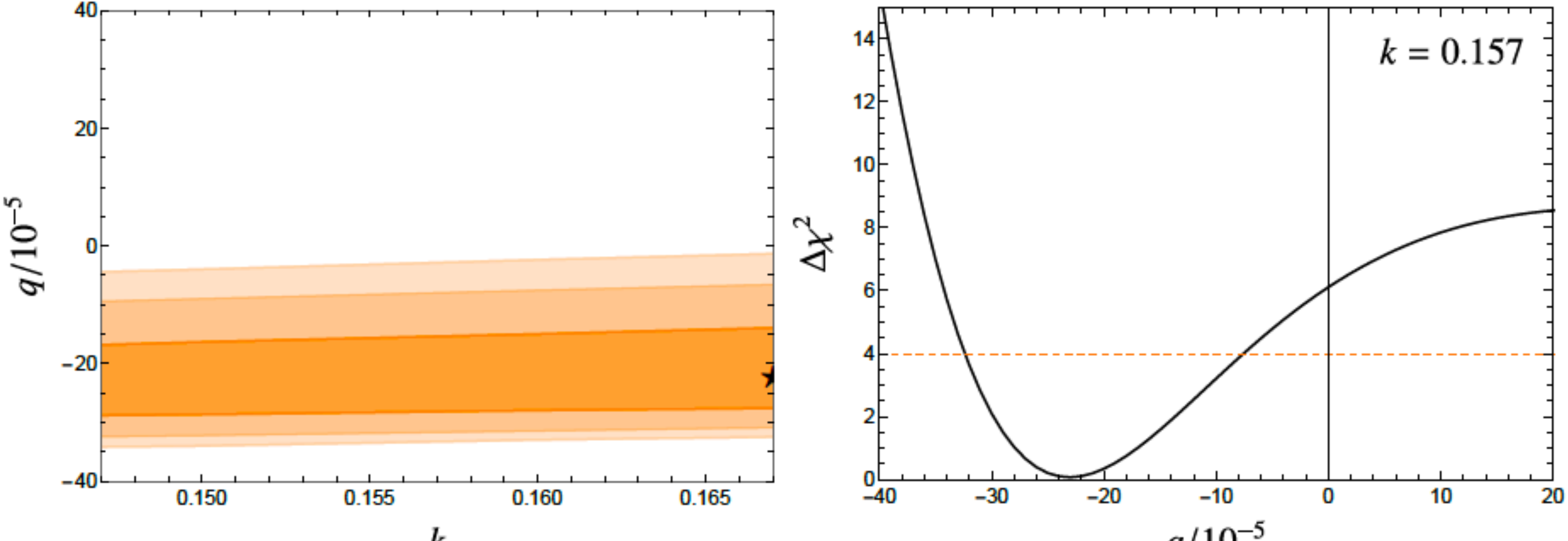
NCC-1701 is a 3 kg Ge detector placed 10 m from 2.96 GW Dresden-II power reactor



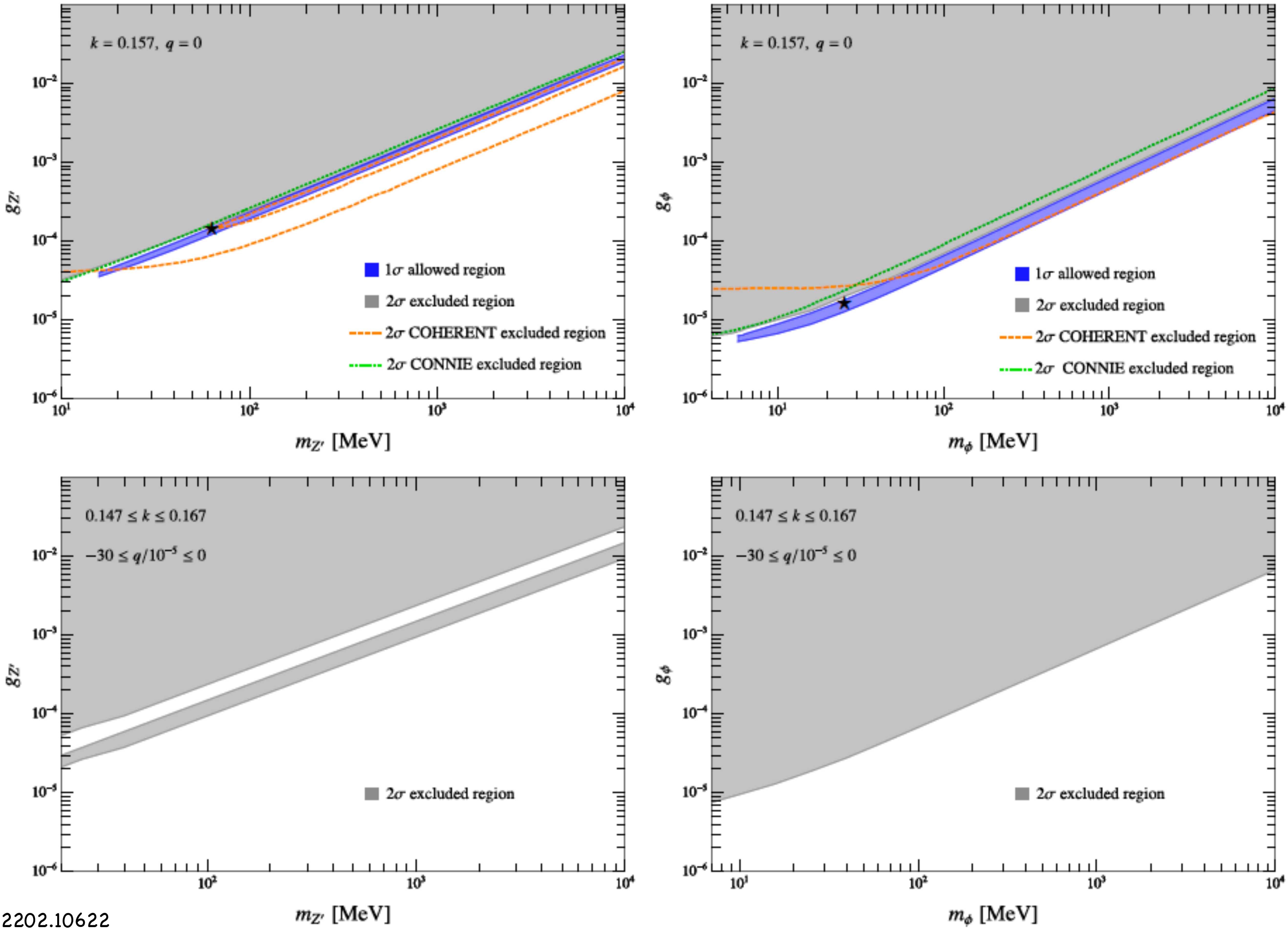
2202.09672


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

2202.10622


40
20
0
−20
−40
$q/10^{-5}$
0.150
0.155
0.160
0.165
k
$k = 0.157$
14
12
10
8
6
4
2
0
$\Delta\chi^2$
−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]
$0.147 \leq k \leq 0.167$
$-30 \leq q/10^{-5} \leq 0$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
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

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

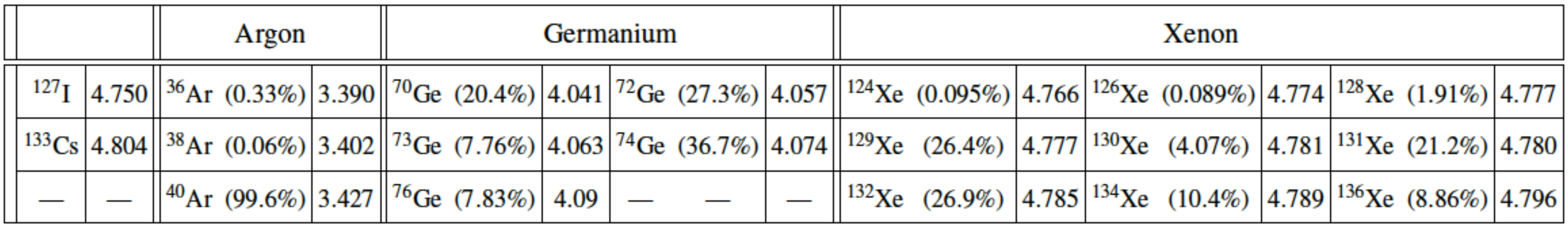
$$\langle r^2\rangle_{\mathrm{SF}} = \frac{3}{5}c^2 + \frac{7}{5}(\pi a)^2$$

- 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		Germanium				Xenon					
^{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

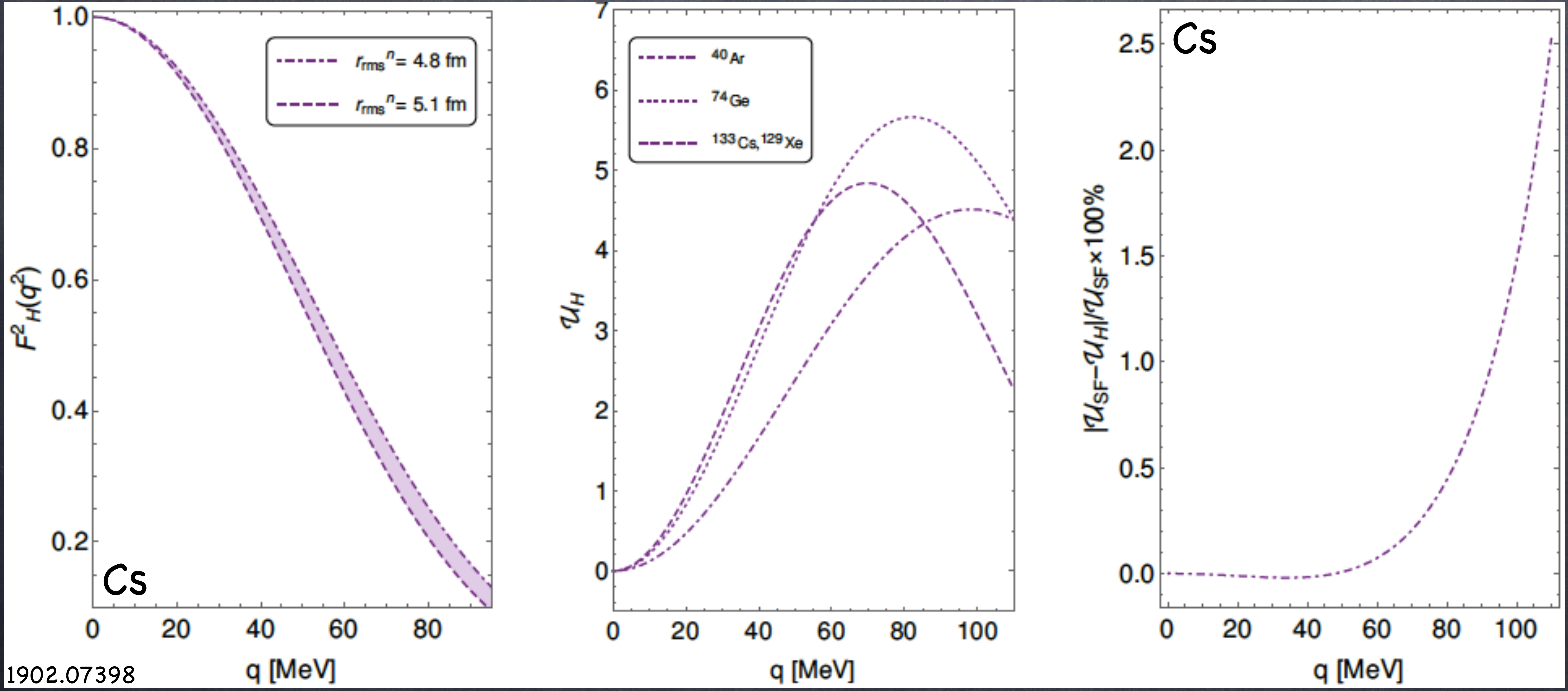
- For neutrons, do the same except allow neutron rms radius to vary within r_p and r_p+0.3 fm for Cs, I, Ge, Xe since neutron skin of Pb is

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

- … and within r_p and either r_p+0.1 fm or r_p+0.2 fm for Ar

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

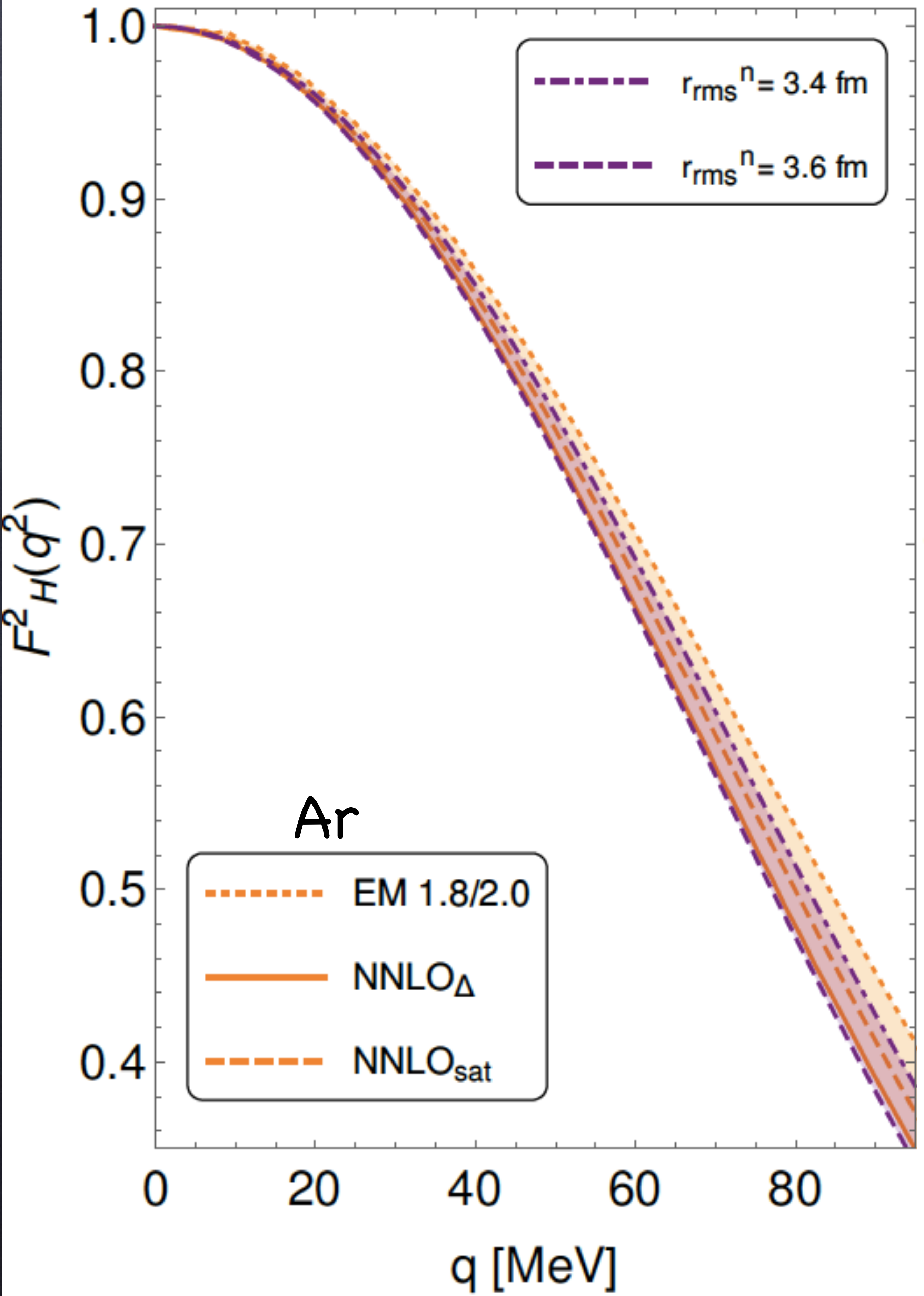
+ 0.2 fm for Ar

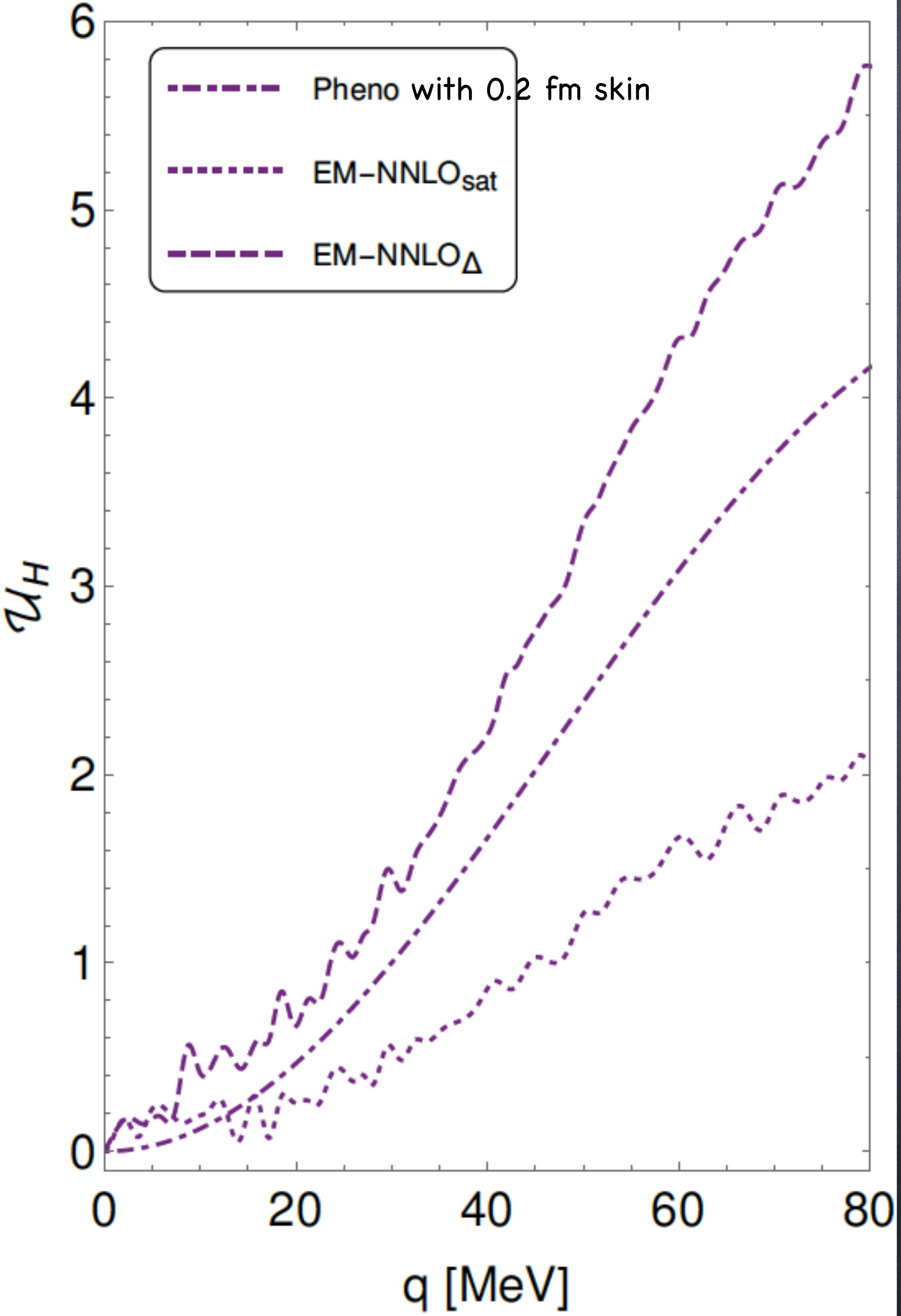


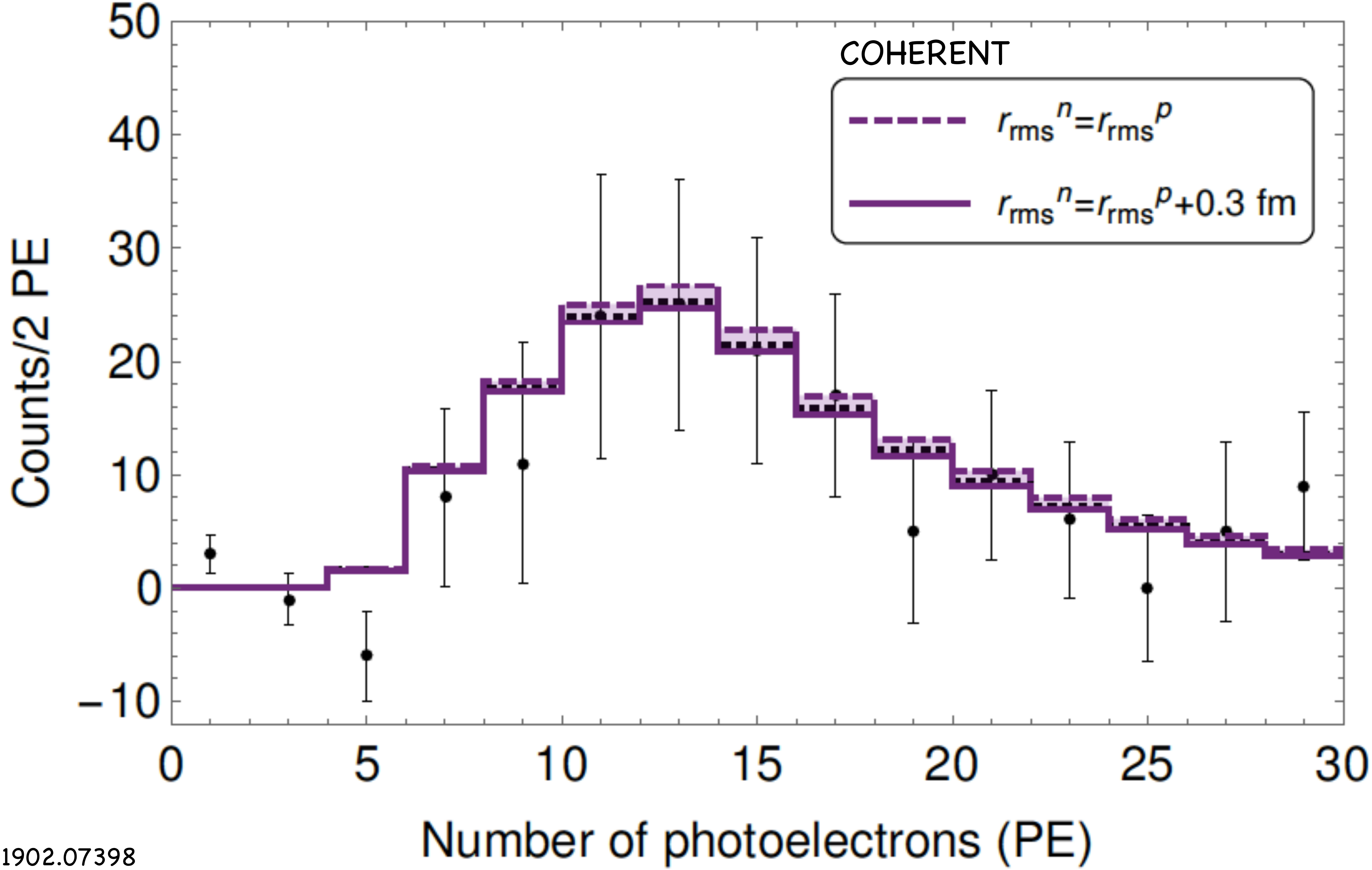
1902.07398

Size of the uncertainties do not depend on the FF chosen

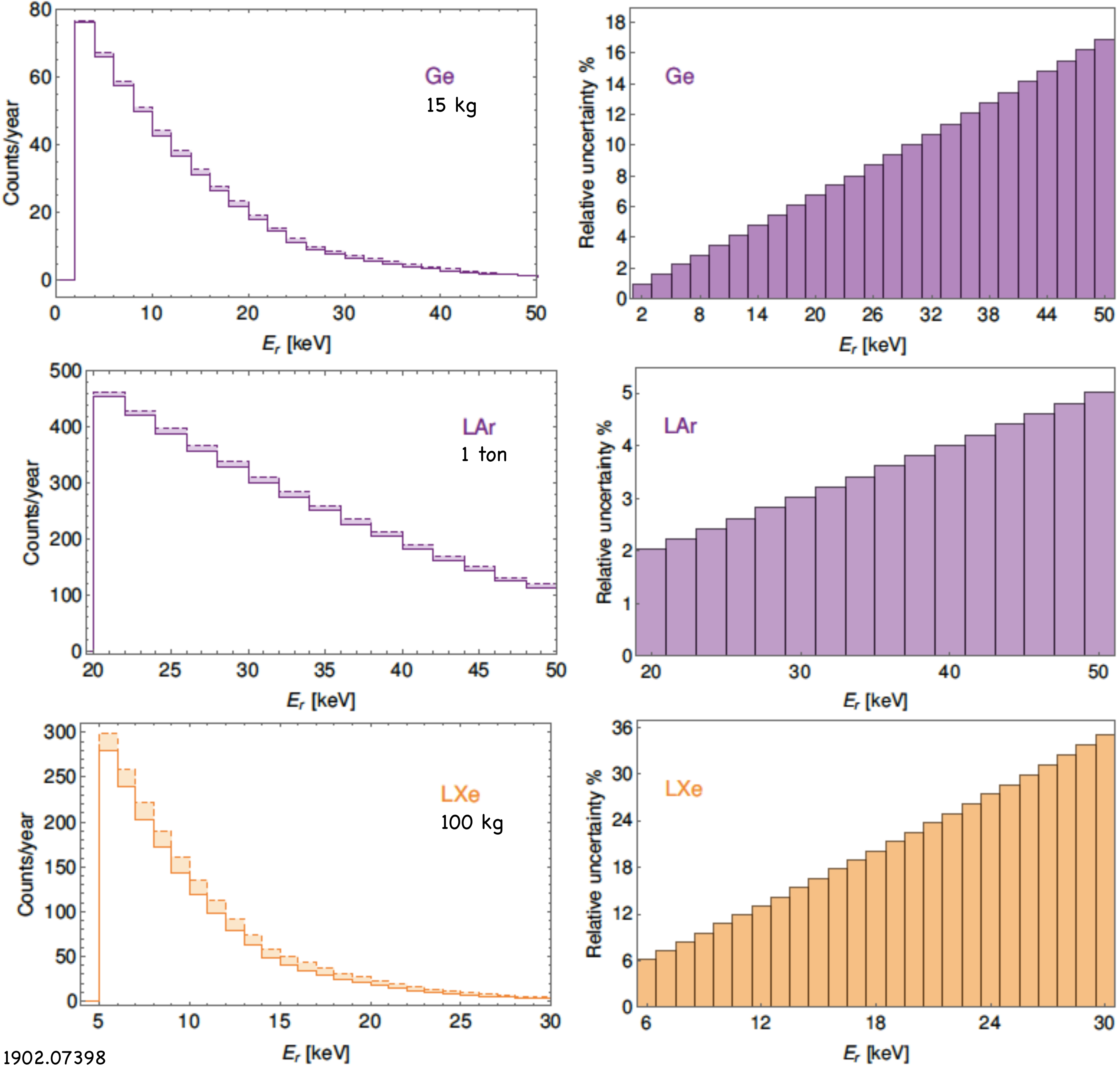
Hagen FFs


$r_{rms}{}^n$= 3.4 fm
$r_{rms}{}^n$= 3.6 fm
Ar
EM 1.8/2.0
NNLO$_\Delta$
NNLO$_{sat}$
$F^2{}_H(q^2)$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0
20
40
60
80
q [MeV]


Pheno with 0.2 fm skin
EM−NNLO$_{sat}$
EM−NNLO$_\Delta$
$\mathcal{U}_H$
6
5
4
3
2
1
0
0
20
40
60
80
q [MeV]

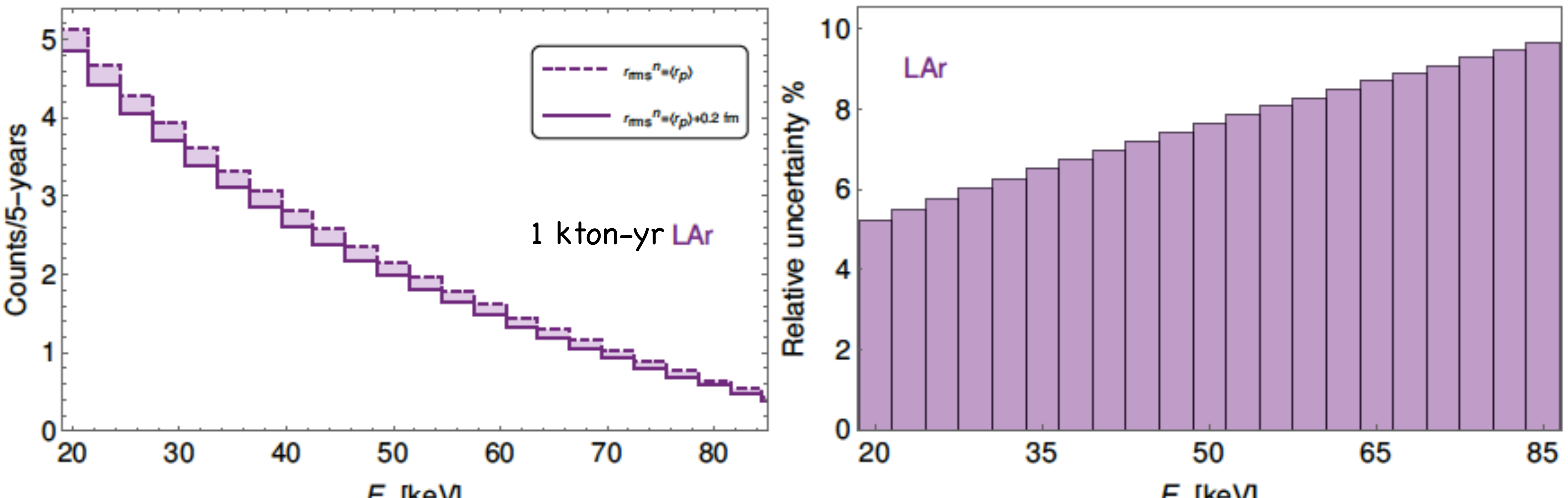

COHERENT
$r_{\text{rms}}{}^{n}=r_{\text{rms}}{}^{p}$
$r_{\text{rms}}{}^{n}=r_{\text{rms}}{}^{p}+0.3$ fm
Counts/2 PE
50
40
30
20
10
0
−10
0
5
10
15
20
25
30
Number of photoelectrons (PE)

1902.07398


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

1902.07398

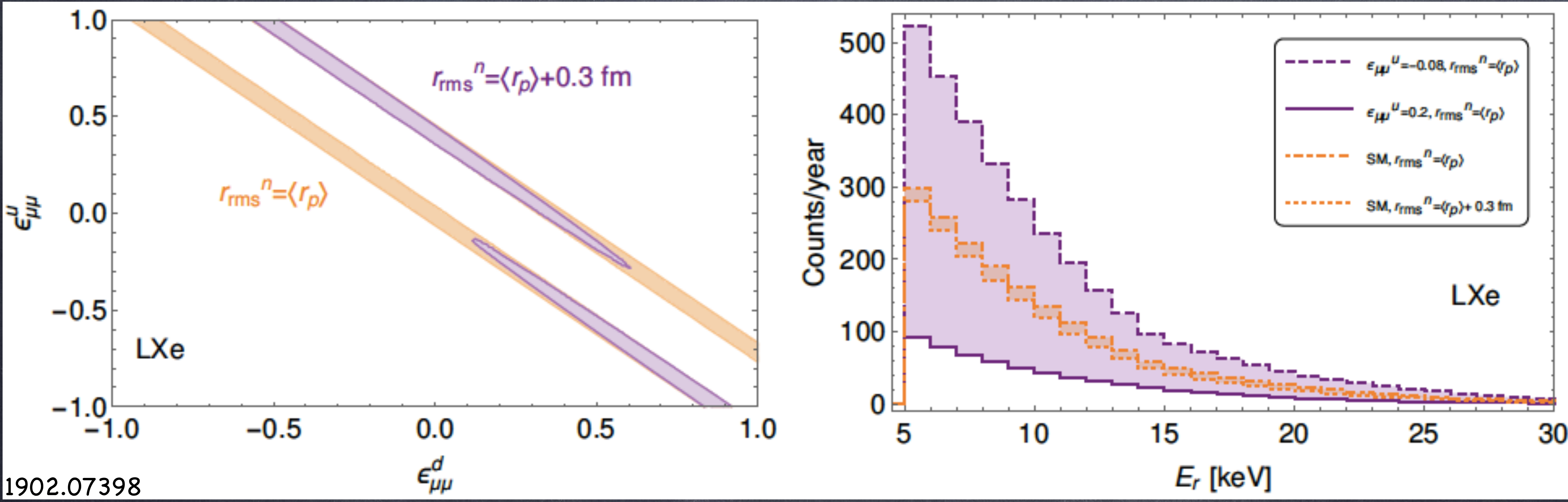
Backgrounds to dark matter searches



1 kton-yr LAr

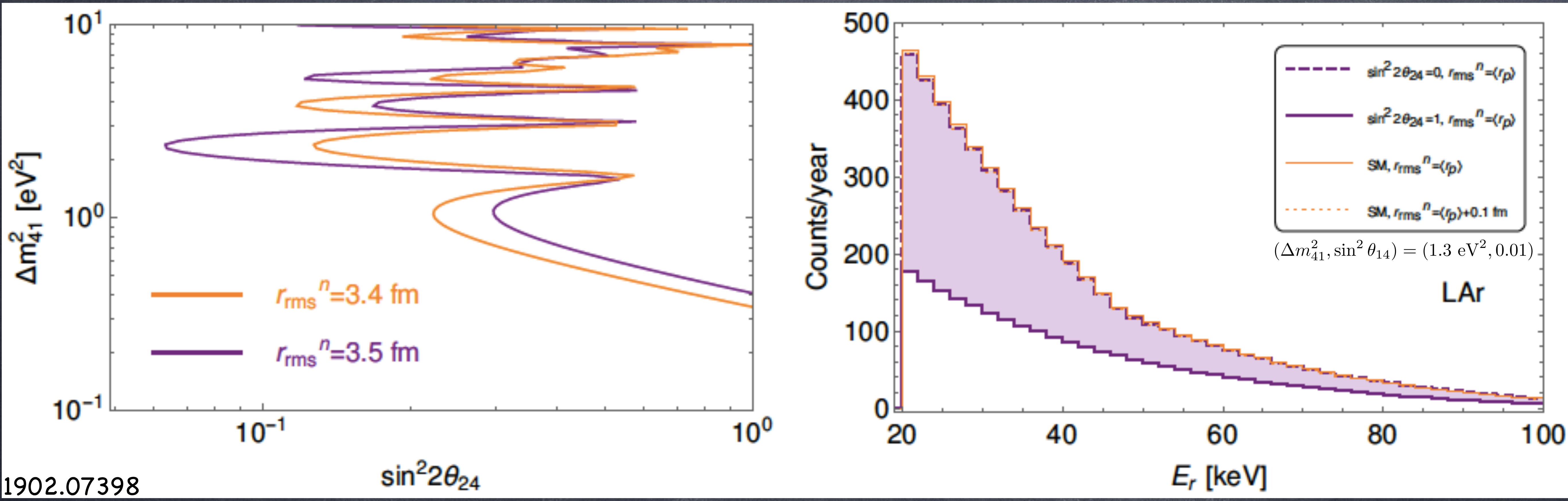
1902.07398

NSI



1902.07398

3+1 sterile neutrino oscillations

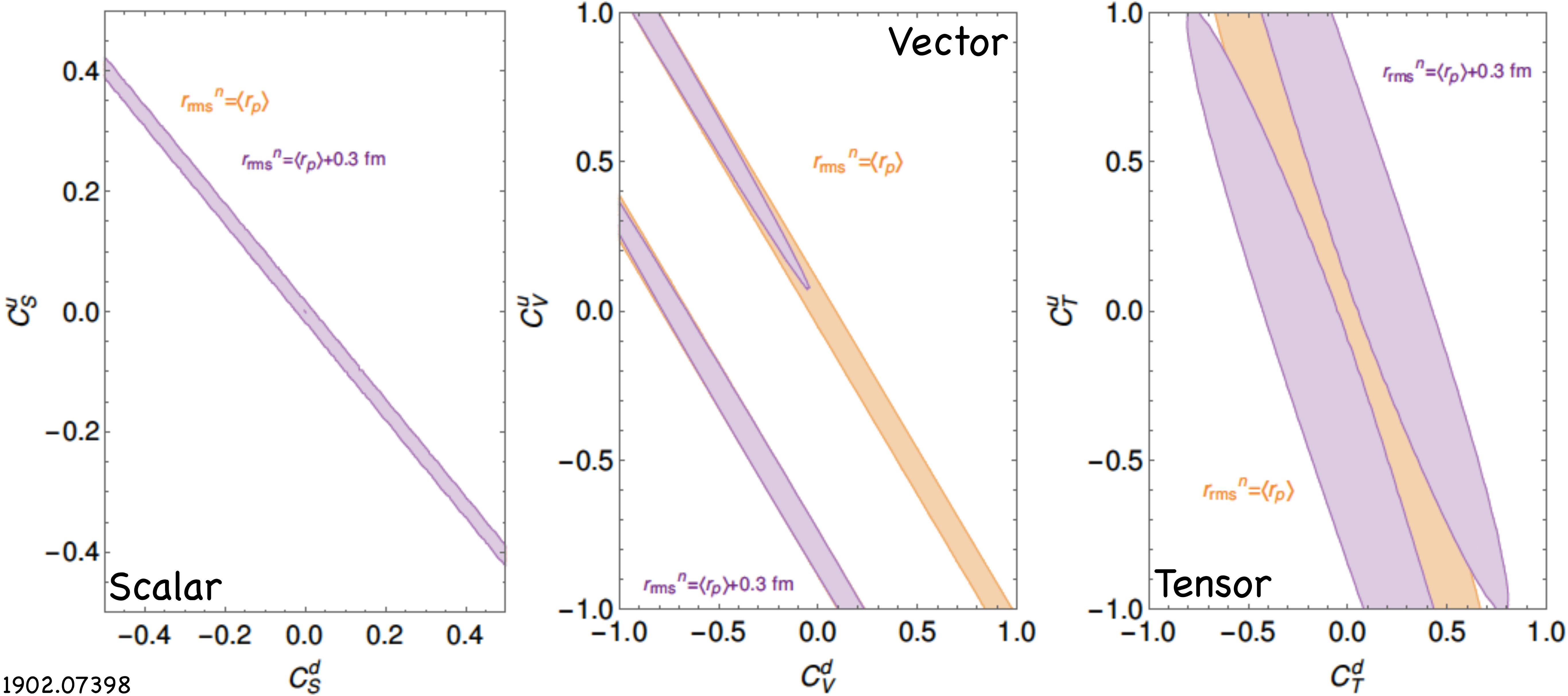


1902.07398

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

Neutrino generalized interactions

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



1902.07398

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