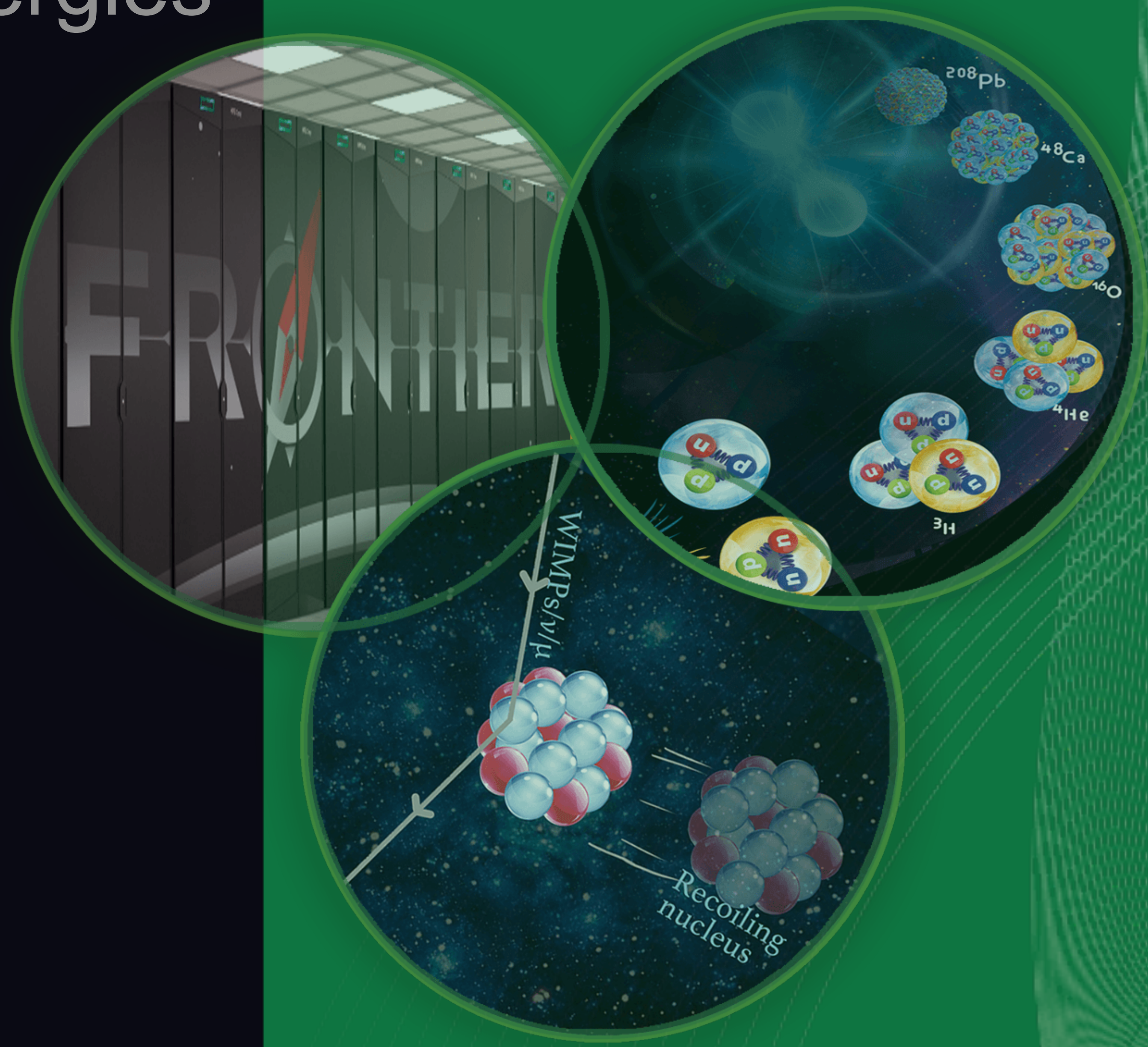
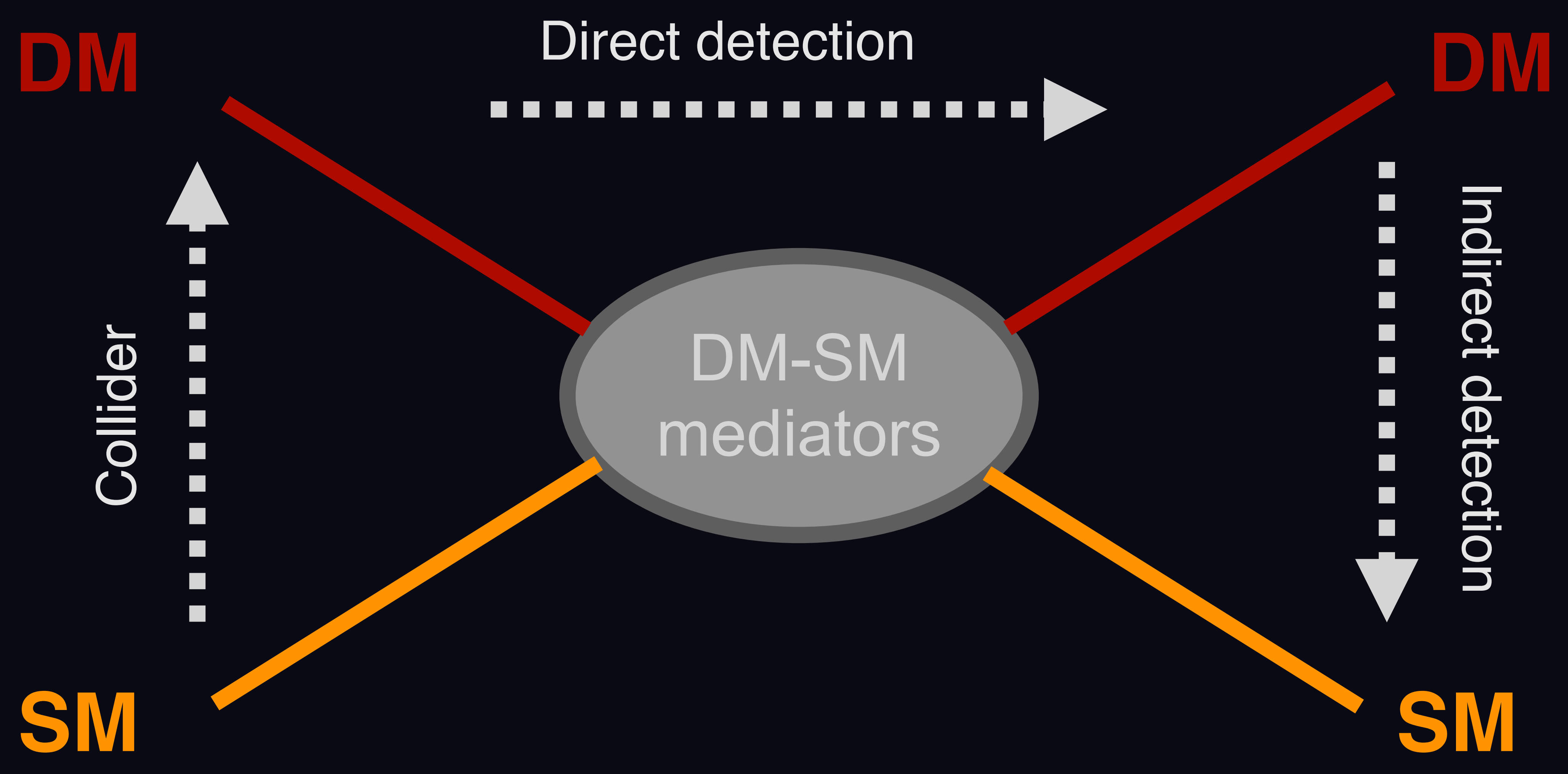
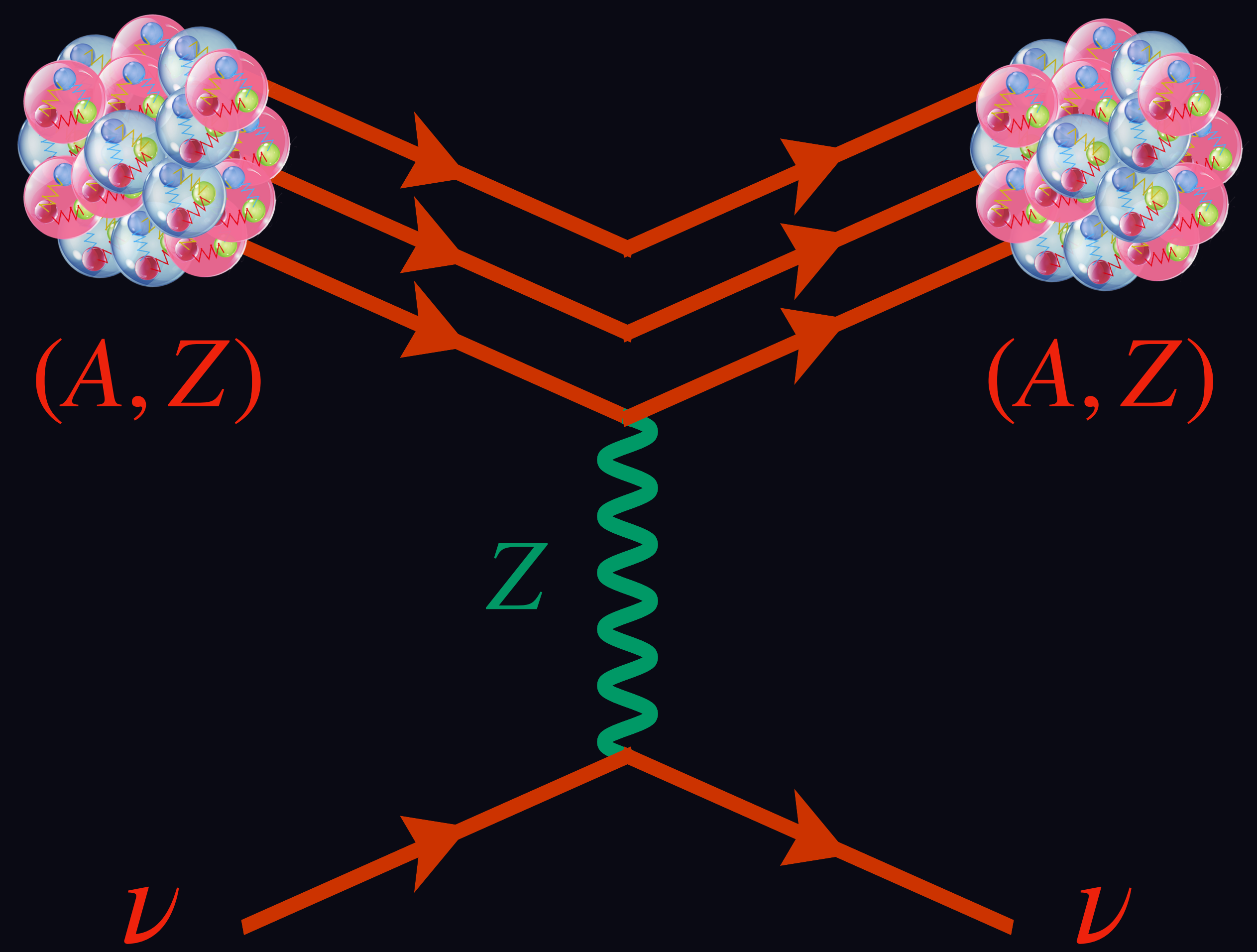


Ab initio Nuclear Calculations for Dark Matter Detection and CEvNS

Bai-Shan Hu (胡柏山)
bhu1@ornl.gov

April 17, 2023 @ Seattle





OAK RIDGE National Laboratory

Outline

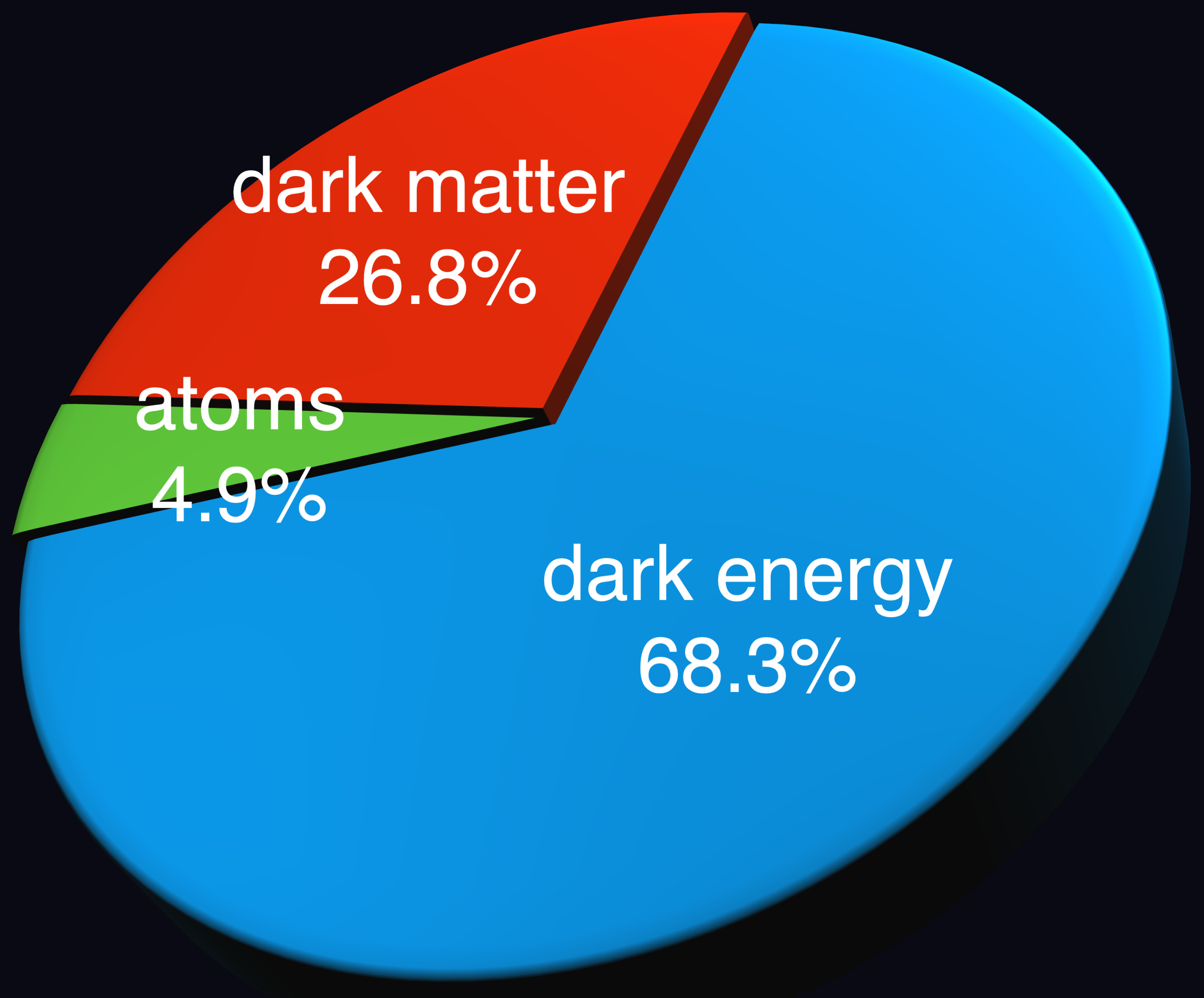
Theoretical steps for WIMP/v scattering off nuclei

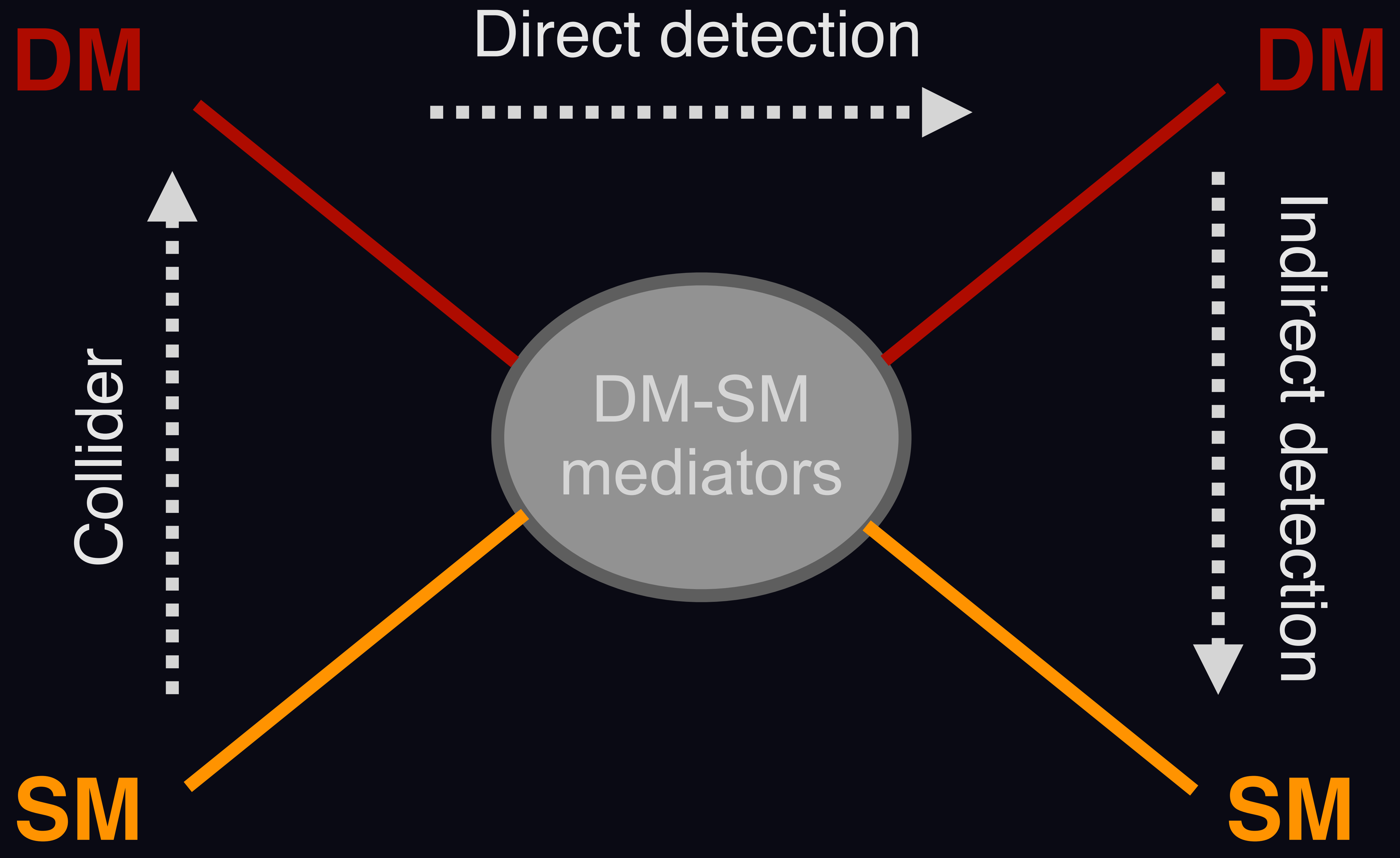
VS-IMSRG calculations for elastic spin-dependent WIMP scattering and CEvNS (Chiral EFT: 1b + 2b currents)

Outlook: Spin-independent WIMP scattering;
Inelastic

Part I

How to search for DM?





WIMP χ scattering elastically off nucleus $\mathcal{N}$

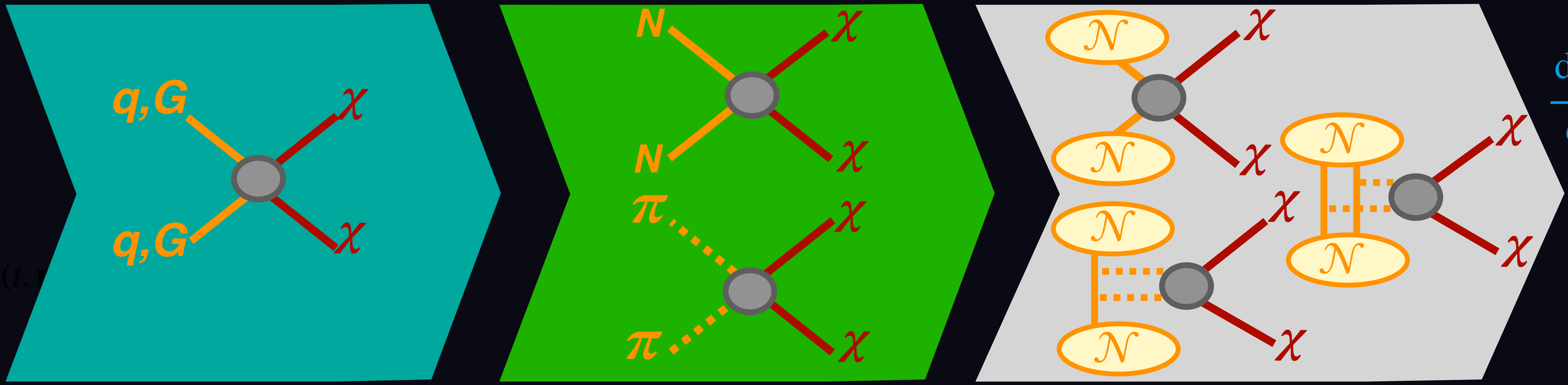
$$\mathcal{N}(p) + \chi(k) \to \mathcal{N}(p') + \chi(k')$$

$$q = k' - k = p - p', \quad q^2 = t$$

$$\frac{dR}{dE_r} = MT\rho_0 \underbrace{\int_{v_{min}}^{v_{esc}} \frac{f(v)}{v} d^3v}_{\text{astrophysics}} \times \underbrace{\frac{\sigma_{\chi N}^{SD/SI}}{m_\chi \mu_N^2}}_{\text{particle+hadronic physics}} \times \underbrace{\left| \mathcal{F}^{SD/SI}(\mathbf{q}^2) \right|^2}_{\text{nuclear physics}}$$

astrophysics particle+hadronic physics nuclear physics $\langle \mathcal{N} | H_{\chi A} | \mathcal{N} \rangle$

Calculation for direct detection of dark matter



$$\frac{d\sigma_{\chi\mathcal{N}}}{d\mathbf{q}^2} = \frac{m_N}{2v^2\mu^2} \times \left[\sigma_{SI}\mathcal{F}^2_{SI}\left(\mathbf{q}^2\right) + \sigma_{SD}\mathcal{F}^2_{SD}\left(\mathbf{q}^2\right)\right]$$

Effective Lagrangian $\mathcal{L}_\chi$
DoF: quarks and gluons

Hadronic scale

- **Chiral EFT**
  DoF: nucleons and pions
  meson-exchange currents
- **NREFT**
  DoF: nucleons

$$H_{\chi A} = \sum_{i=1}^{A} \sum_{\tau=0,1} \sum_{j} c_j^\tau \hat{\mathcal{O}}_j^{(i)} t_{(i)}^\tau$$

Nuclear scale

DoF: nucleons (p and n)
nuclear wavefunction $\langle \mathcal{N} | H_{\chi A} | \mathcal{N} \rangle$

- **Shell model**
  commonly used
  not all nucleons active
  no consistent effective operator
  no consistent LECs with nuclear force
- **Ab initio method**

This talk will focus on spin-dependent case

$$\mathscr{L}_\chi^{\mathrm{SD}} = -\frac{G_F}{\sqrt{2}}\int d^3\mathbf{r}\,\bar{\chi}\gamma\gamma_5\chi\cdot\sum_q C_q^{AA}\bar{q}\gamma\gamma_5 q$$

one-nucleon level — isoscalar — isovector

$$\sum_q C_q^{AA}\bar{q}\gamma\gamma_5 q \;\rightarrow\; \mathbf{J}_{i,1\mathrm{b}} = \mathbf{J}^+_{i,1\mathrm{b}} + \mathbf{J}^-_{i,1\mathrm{b}}$$

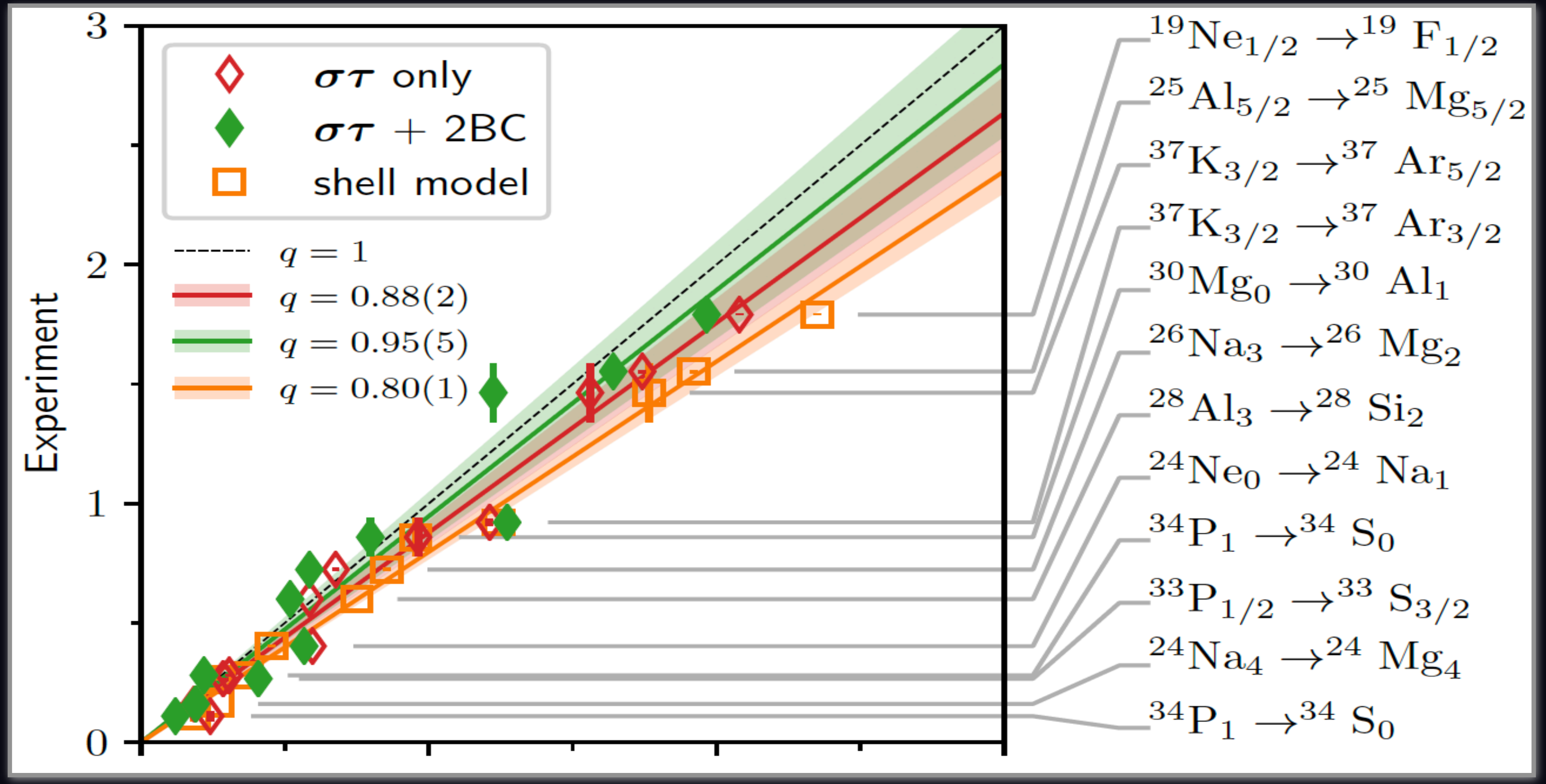
- one-body currents

loop corrections — pion propagators

$$\sum_{i=1}^{A}\mathbf{J}_{i,1\mathrm{b}} = \sum_{i=1}^{A}\frac{1}{2}\left[a_+\sigma_i + a_-\tau_i^3\left(\frac{g_A(p^2)}{g_A}\sigma_i - \frac{g_P(p^2)}{2m g_A}(\mathbf{p}\cdot\sigma_i)\,\mathbf{p}\right)\right]$$

- two-body currents

$$\mathbf{J}_{2b}^{-} = -\frac{g_A}{2F_\pi^2}[\tau_1\times\tau_2]^3\left[c_4\left(1-\frac{\mathbf{q}}{\mathbf{q}^2+M_\pi^2}\mathbf{q}\cdot\right)(\boldsymbol{\sigma}_1\times\mathbf{k}_2) + \frac{c_6}{4}(\boldsymbol{\sigma}_1\times\mathbf{q}) + i\frac{\mathbf{p}_1+\mathbf{p}_1'}{4m_N}\right]\frac{\boldsymbol{\sigma}_2\cdot\mathbf{k}_2}{M_\pi^2+k_2^2}$$
$$-\frac{g_A}{F_\pi^2}\tau_2^3\left[c_3\left(1-\frac{\mathbf{q}}{\mathbf{q}^2+M_\pi^2}\mathbf{q}\cdot\right)\mathbf{k}_2 + 2c_1M_\pi^2\frac{\mathbf{q}}{\mathbf{q}^2+M_\pi^2}\right]\frac{\boldsymbol{\sigma}_2\cdot\mathbf{k}_2}{M_\pi^2+k_2^2}$$
$$-d_1\tau_1^3\left(1-\frac{\mathbf{q}}{\mathbf{q}^2+M_\pi^2}\mathbf{q}\cdot\right)\boldsymbol{\sigma}_1 + (1\leftrightarrow 2) - d_2(\tau_1\times\tau_2)^3(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\left(1-\mathbf{q}\frac{\mathbf{q}}{\mathbf{q}^2+M_\pi^2}\right)$$



P Gysbers, et al., Nat. Phys. 15 (2019) 428

include as density-dependent one-body currents (normal ordering)

Details:
P. Klos, et al., PRD 88 (2013) 083516; 89 (2014) 029901(E)
M. Hoferichter et al., PRD 102 (2020) 074018

Structure factors required from nuclear many-body theory

$$\frac{d\sigma_{\chi\mathcal{N}}}{d\mathbf{q}^2} = \frac{\zeta^2}{(2J_i+1)\,\pi v^2}\sum_{s_f,s_i}\sum_{M_f,M_i}\left|\left\langle \mathcal{N}_f \middle| \mathcal{L}_\chi^{\mathrm{SD}} \middle| \mathcal{N}_i \right\rangle\right|^2 = \frac{8G_F^2\zeta^2}{v^2\,(2J_i+1)} S_A(\mathbf{q}^2)$$

- decompose into longitudinal, transverse electric and transverse magnetic

$$S_A(\mathbf{q}^2) = \sum_{L\geqslant 0}\left|\left\langle J_f \| \mathcal{L}_L^5 \| J_i \right\rangle\right|^2 + \sum_{L\geqslant 1}\left(\left|\left\langle J_f \| \mathcal{T}_L^{\mathrm{el}5} \| J_i \right\rangle\right|^2 + \left|\left\langle J_f \| \mathcal{T}_L^{\mathrm{mag}\,5} \| J_i \right\rangle\right|^2\right)$$

$$S_A(q) = a_+^2 S_{00}(q) + a_+a_- S_{01}(q) + a_-^2 S_{11}(q)$$

- q ➔ 0, with proton/neutron spin expectation values $\langle \hat{S}_{p/n} \rangle$

$a_- + a_- \times$ (2b currents effects)

$$S_A(0) = \frac{(2J+1)(J+1)}{4\pi J}\left|(a_+ + a'_-)\left\langle \hat{S}_p \right\rangle + (a_+ - a'_-)\left\langle \hat{S}_n \right\rangle\right|^2$$

- commonly use the structure factors S_p and S_n

proton-only S_p: $a_+ = a_-$

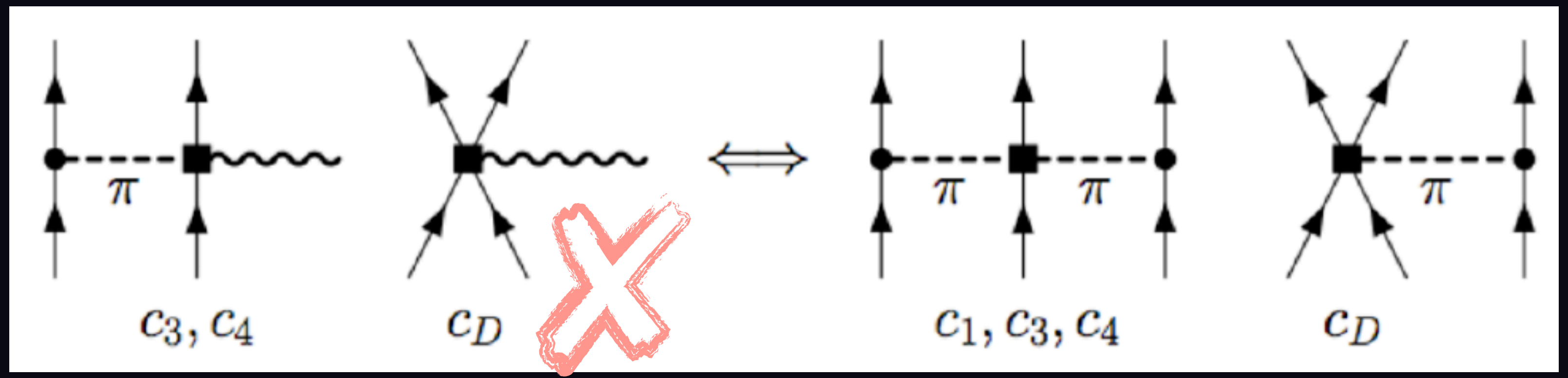
neutron-only S_n: $a_+ = -a_-$

$$S_p(q) = S_{00}(q) + S_{01}(q) + S_{11}(q)$$

$$S_n(q) = S_{00}(q) - S_{01}(q) + S_{11}(q)$$

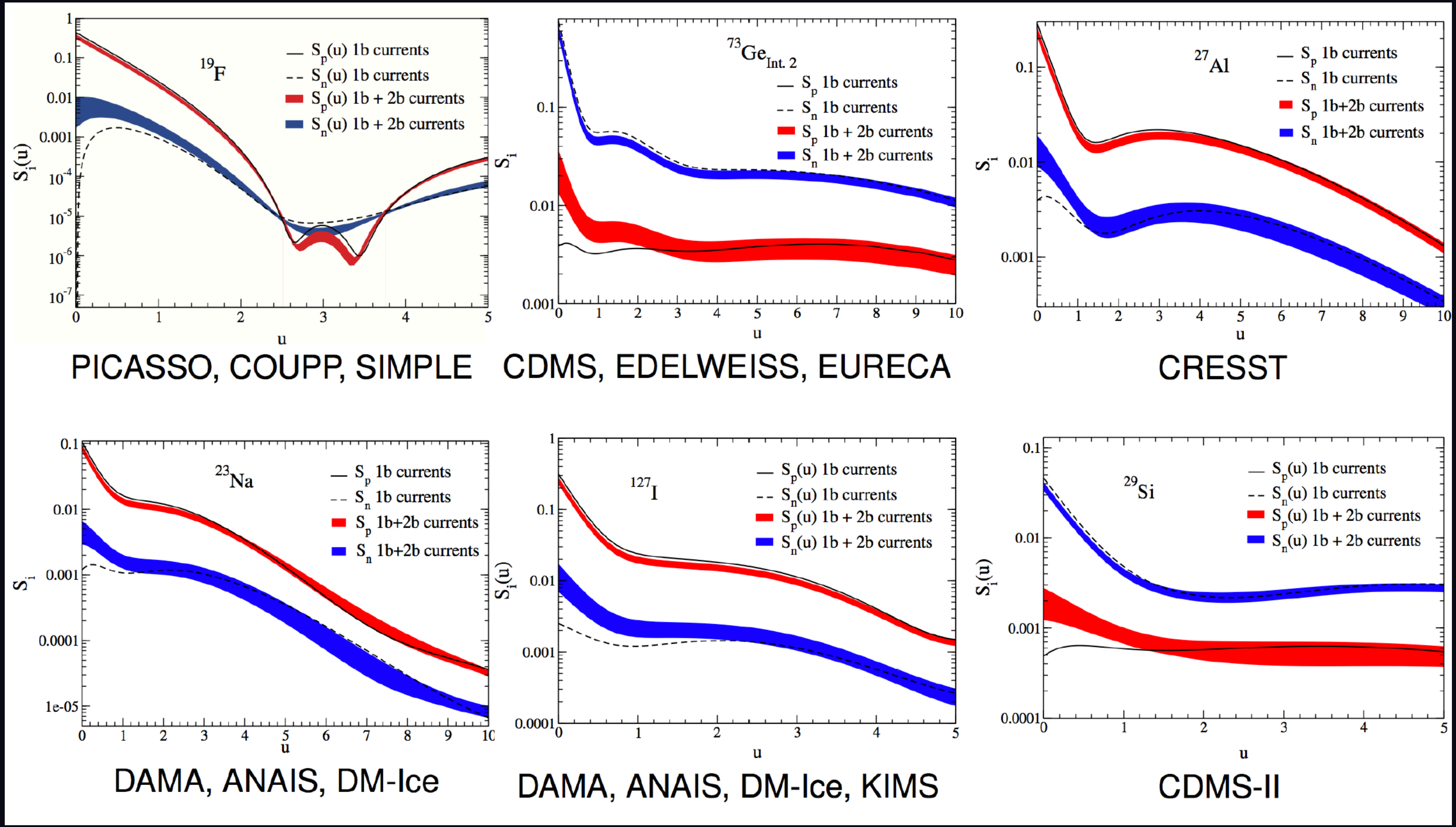
Spin-dependent WIMP-nucleus response

Standard SM: phenomenological wavefunctions + bare operator (with two-body currents of pion exchange)



$C3$ = (-3.2, -2.2, -3.4, -2.4, -4.78, -3.78) GeV^{-1}

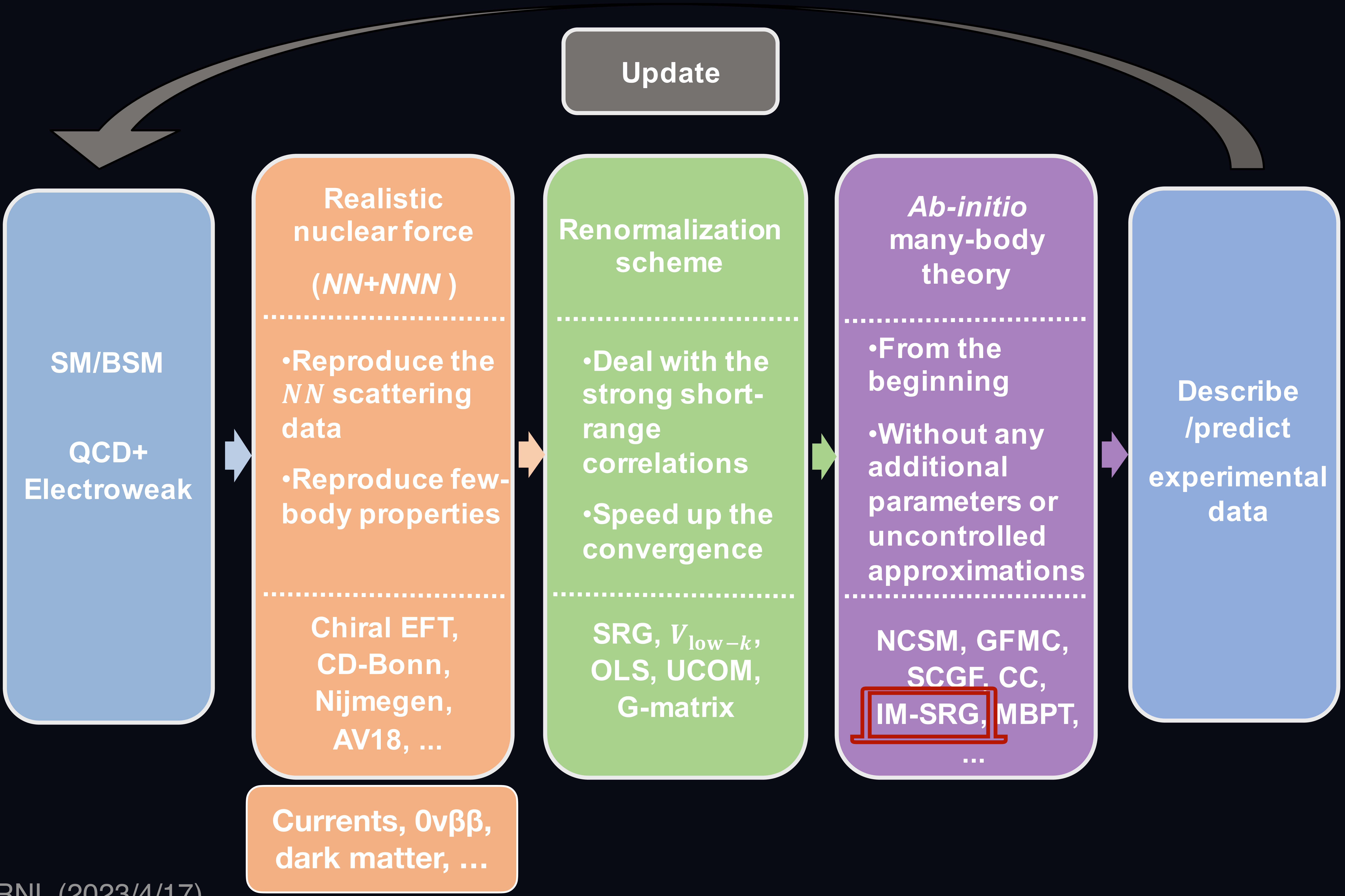
$C4$ = (5.4, 4.4, 3.4, 2.4, 3.96, 2.96) GeV^{-1}



P. Klos, et al., PRD 88 (2013) 083516

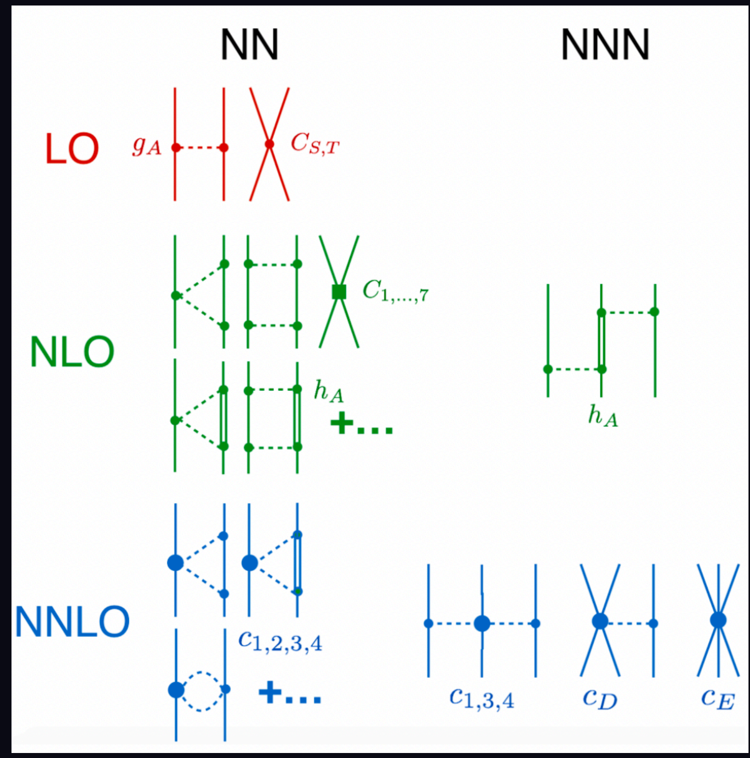
Ab initio calculations ???

Workflow of *ab-initio* nuclear calculation



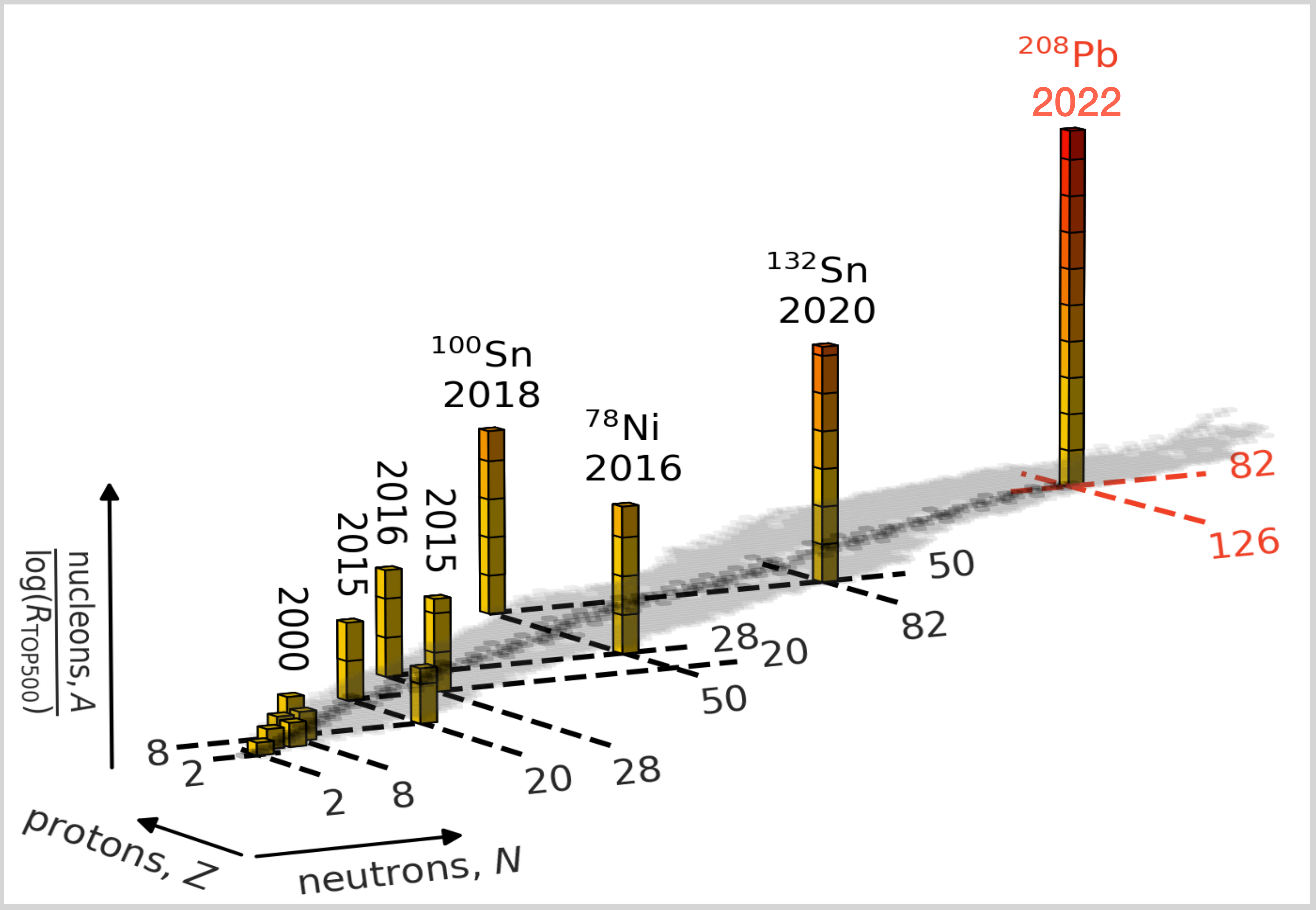
Ab initio results for ^{208}Pb region

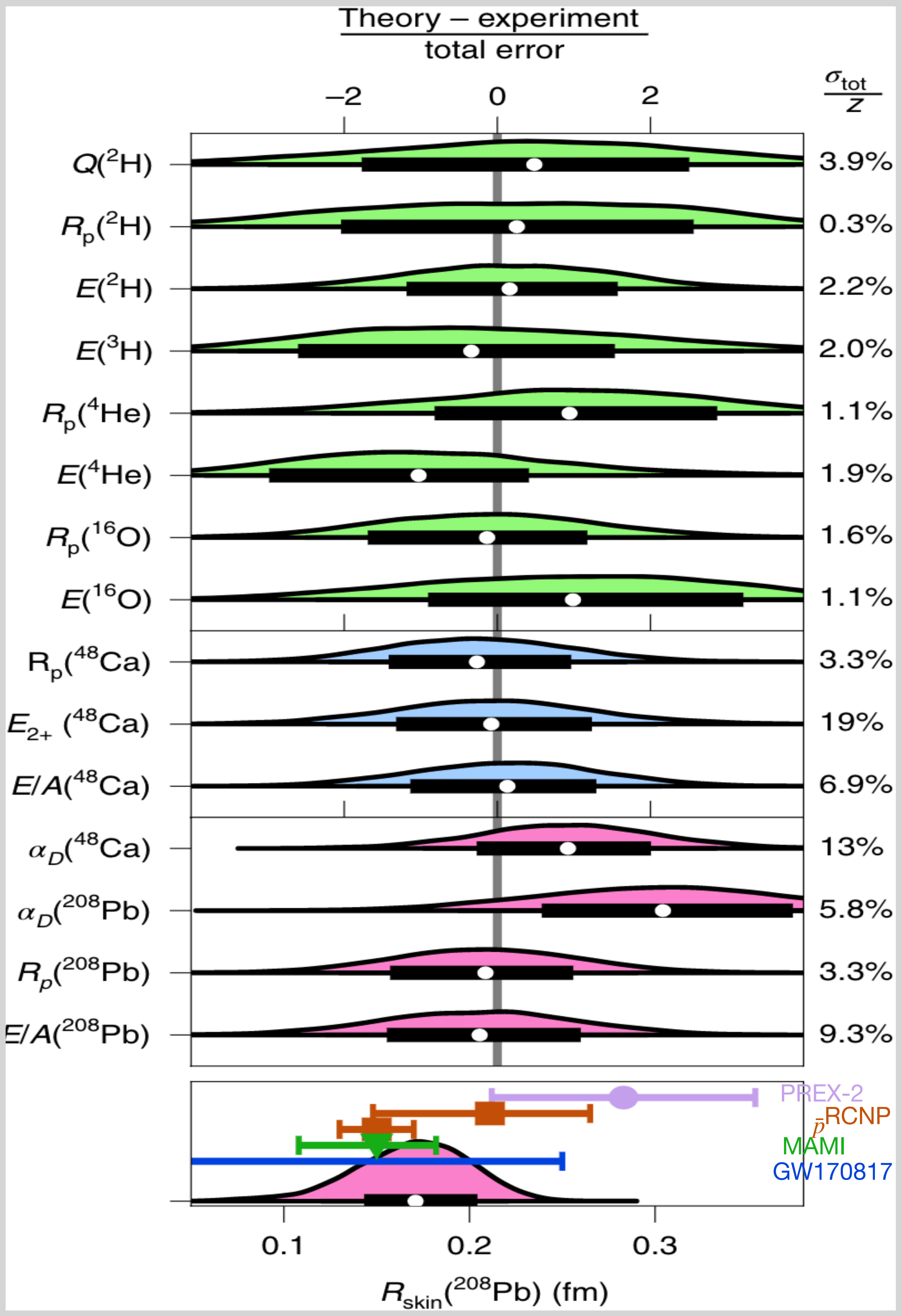
Chiral NN + 3N



History matching
Emulator technology
Statistical tools

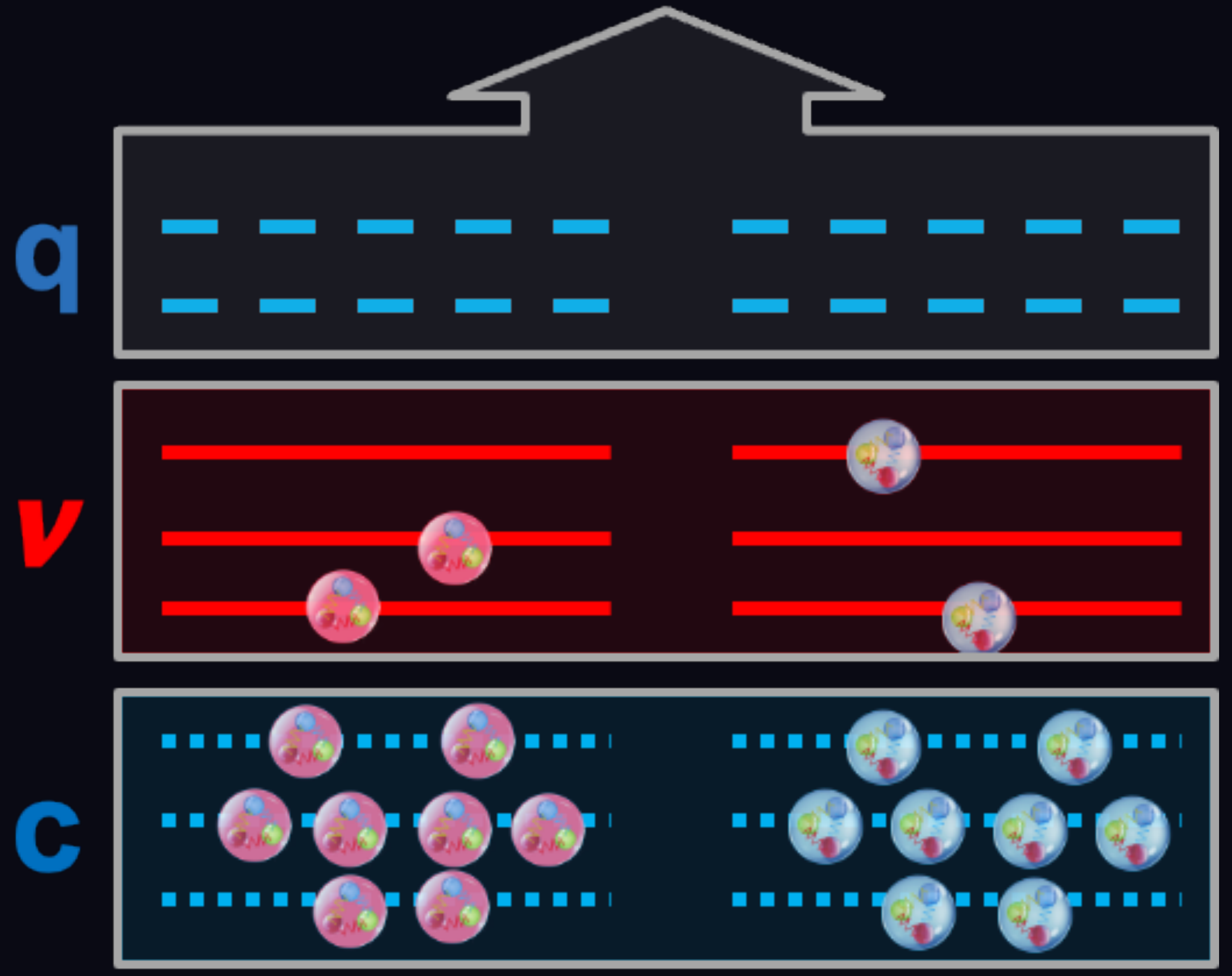
New 3N storage scheme
IMSRG, CC, MBPT





BSHu W.G. Jiang, T. Miyagi, Z.H. Sun, et al., Nat. Phys. 18, 1196 (2022)

Valence-Space In-Medium Similarity Renormalization Group



$$\frac{dH(s)}{ds} = [\eta(s), H(s)]$$

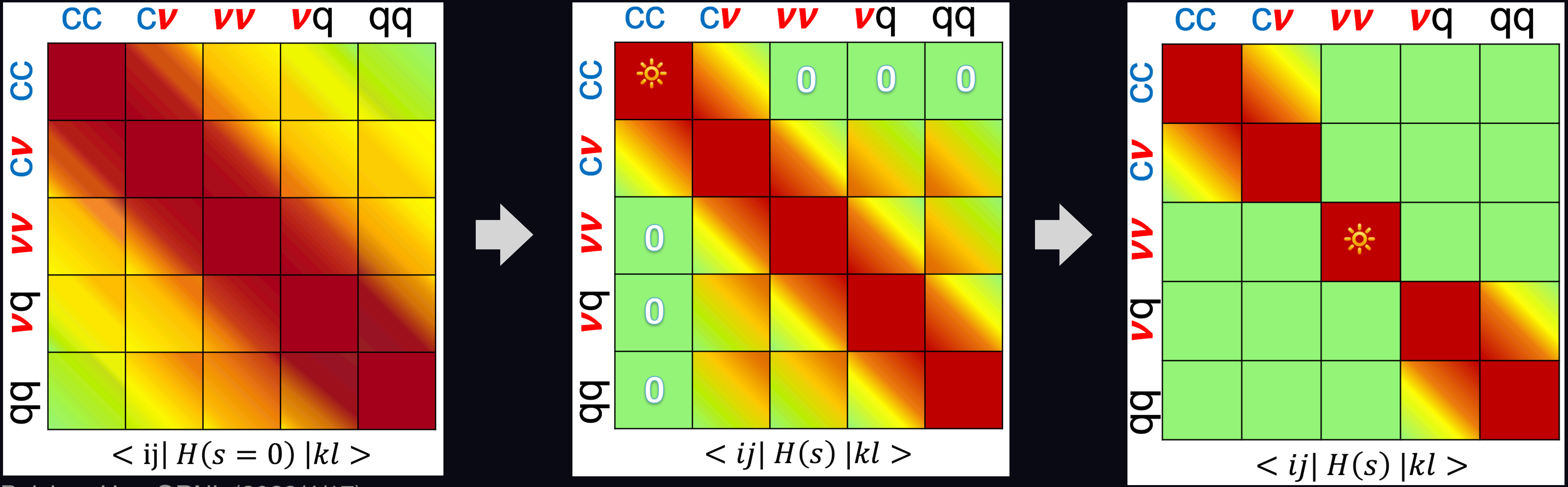
$$H(s) = U(s)HU^{-1}(s) \qquad \mathcal{O}(s) = U(s)\mathcal{O}U^{-1}(s)$$

$$\eta(s) = \frac{dU(s)}{s}U^{\dagger}(s) = -\eta^{\dagger}(s) \qquad U(s) = e^{\Omega(s)}$$

Step1: Decouple core

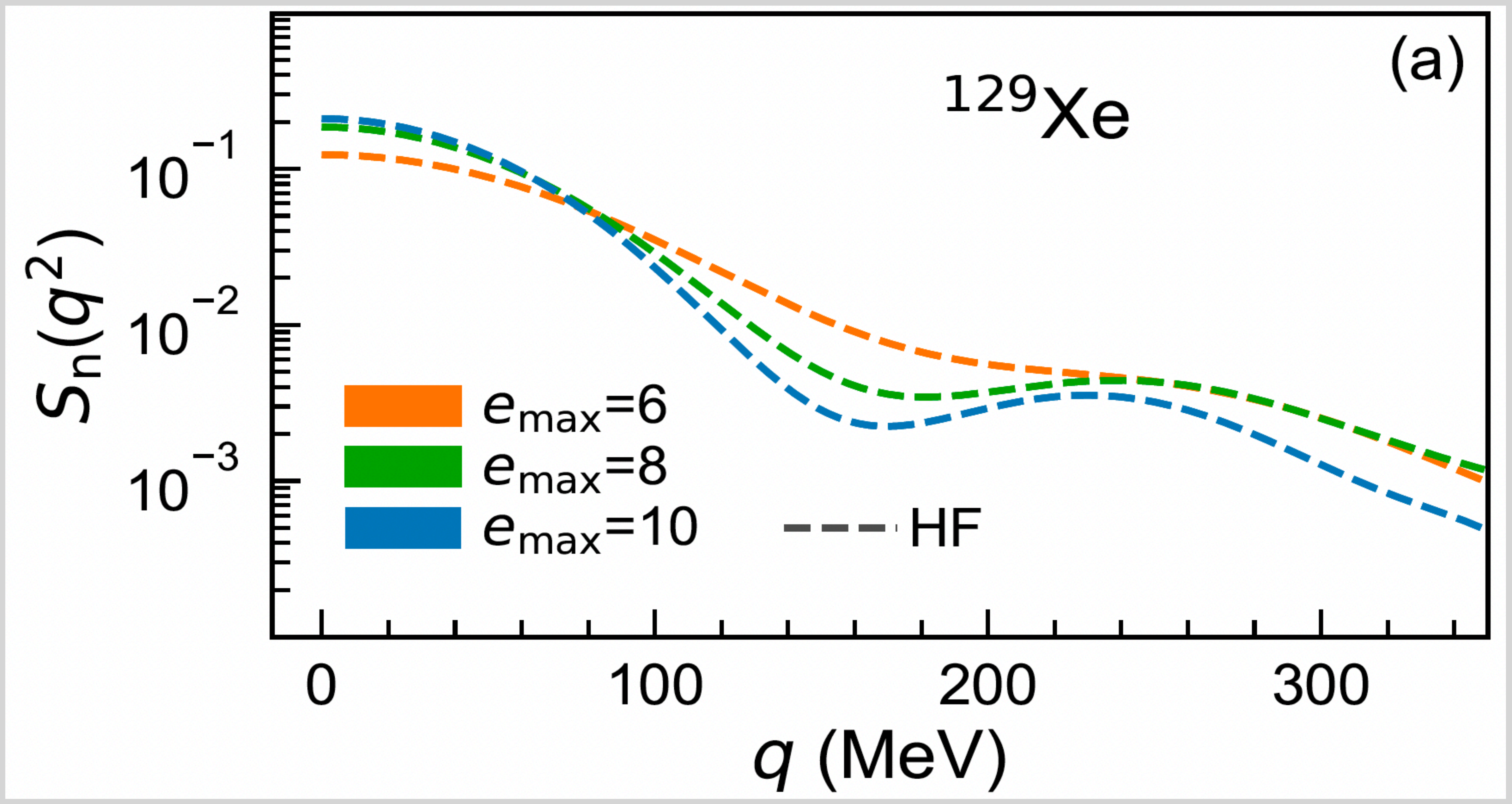
Step2: Decouple valence space

Step3: Decouple additional operators



Heavy nuclei is challenging current *ab initio* approaches

structure factor for spin-dependent dark matter direct detection $\mathcal{F}_{\tau}^{\Sigma'}, \mathcal{F}_{\tau}^{\Sigma''}$



- Tensor operators are very heavy tasks for IMSRG
- Many q points (operators) need to calculate

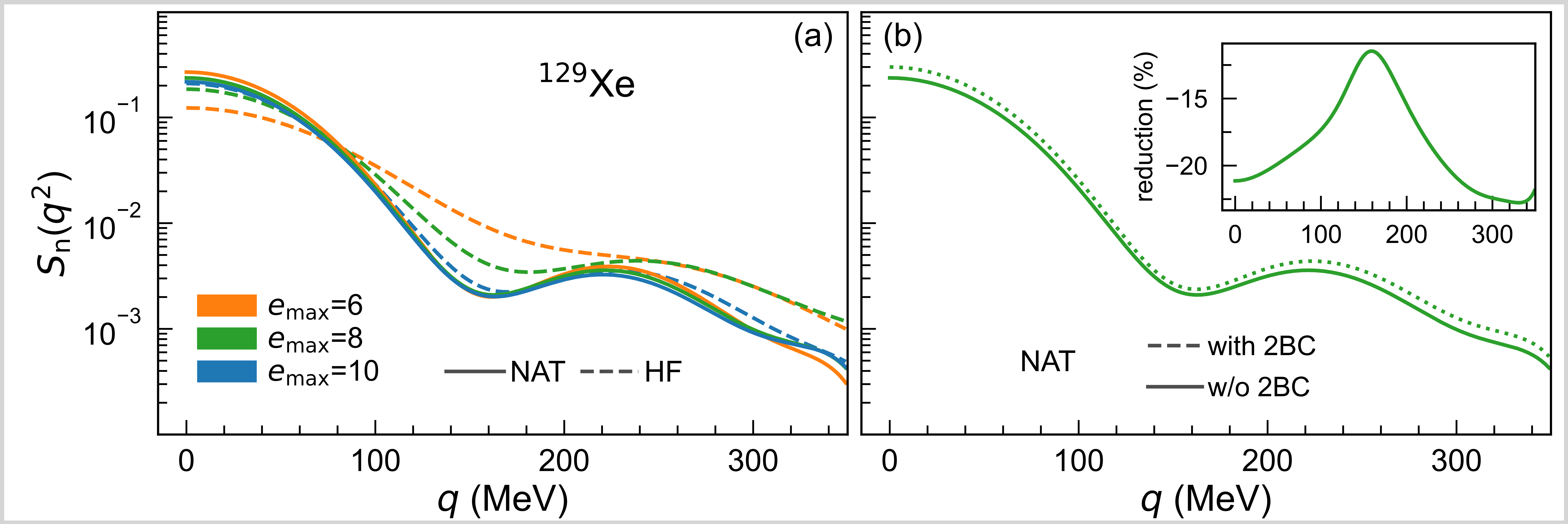
Heavy nuclei is challenging current *ab-initio* approaches

Natural orbitals (NAT)

$$\rho_{pq} = \left\langle \Psi \left| c_p^\dagger c_q \right| \Psi \right\rangle$$

A. Tichai, et al., Phys. Rew. C 99, 034321 (2019)

MBPT ⇨ $|\Psi\rangle \approx \left|\Psi^{(0)}\right\rangle + \left|\Psi^{(1)}\right\rangle + \left|\Psi^{(2)}\right\rangle$

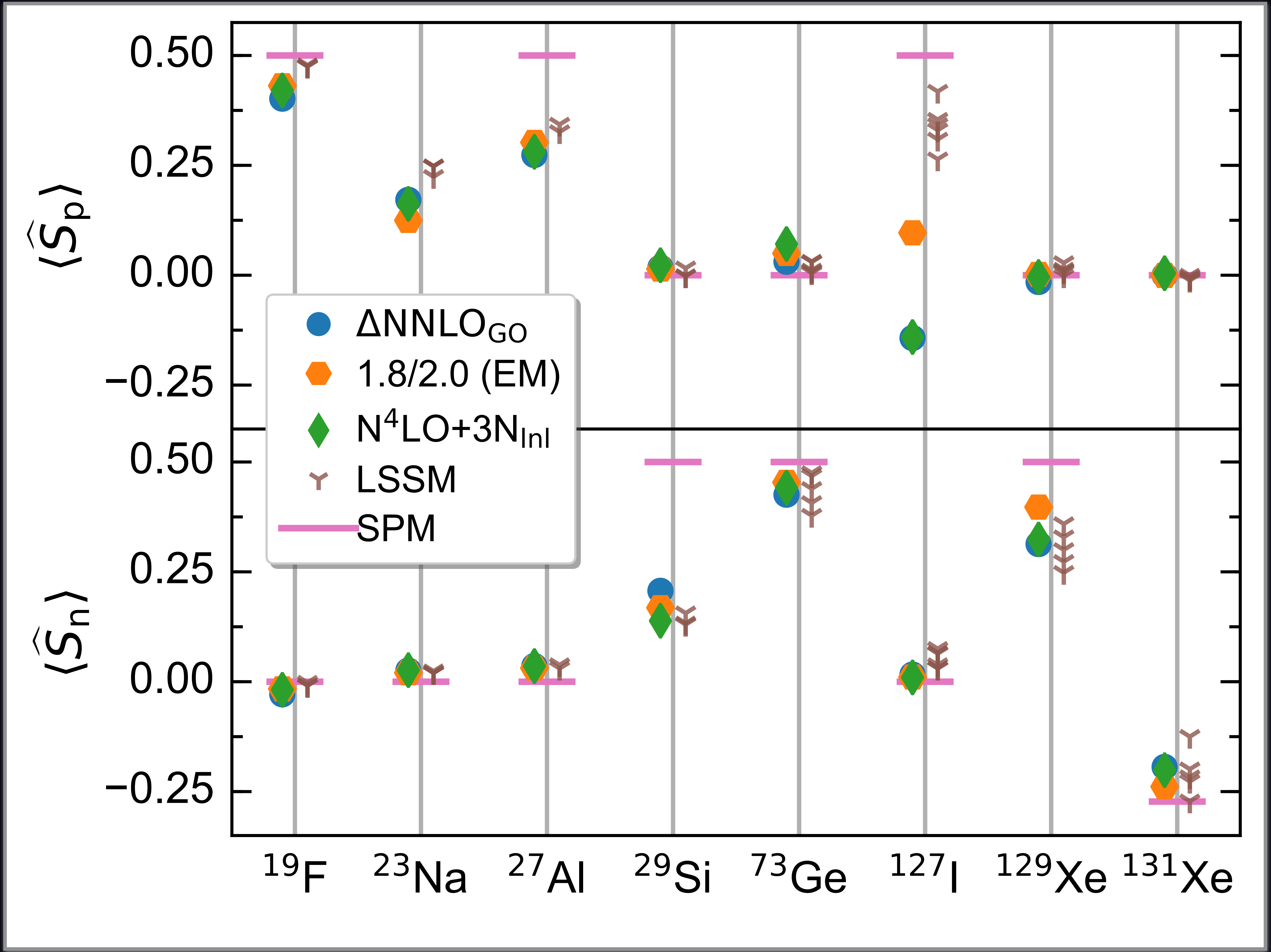


BSH, et al, Phys. Rev. Lett.128, 072502 (2022)

NAT allows VS-IMSRG for heavy nuclei

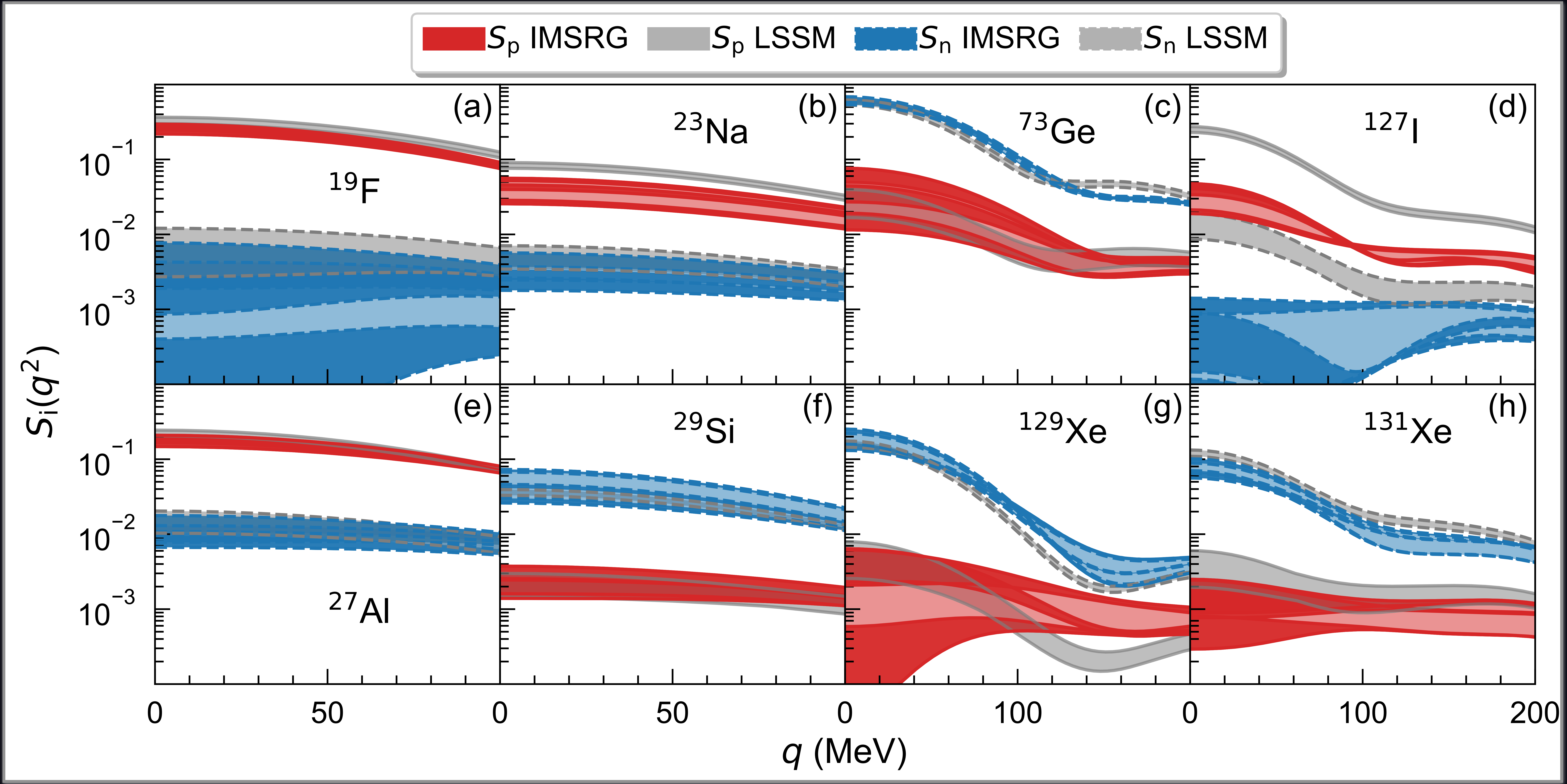
Spin expectation values from VS-IMSRG

$$S_A(0) = \frac{(2J+1)(J+1)}{4\pi J} \left| (a_+ + a'_-) \left\langle \hat{S}_p \right\rangle + (a_+ - a'_-) \left\langle \hat{S}_n \right\rangle \right|^2$$



Shell model results from P. Klos, PRD 88 (2013) 083516

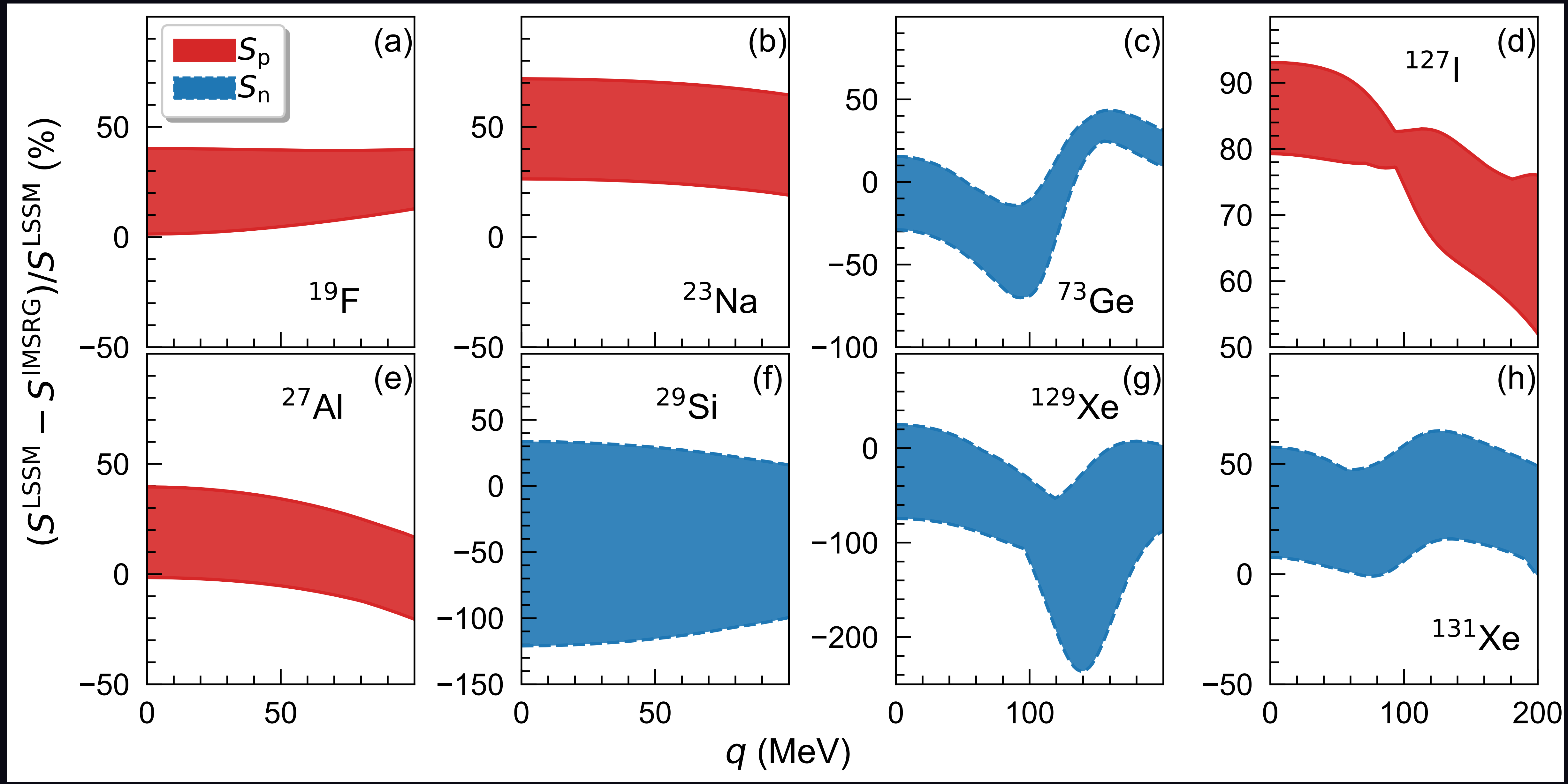
VS-IMSRG results for structure factors



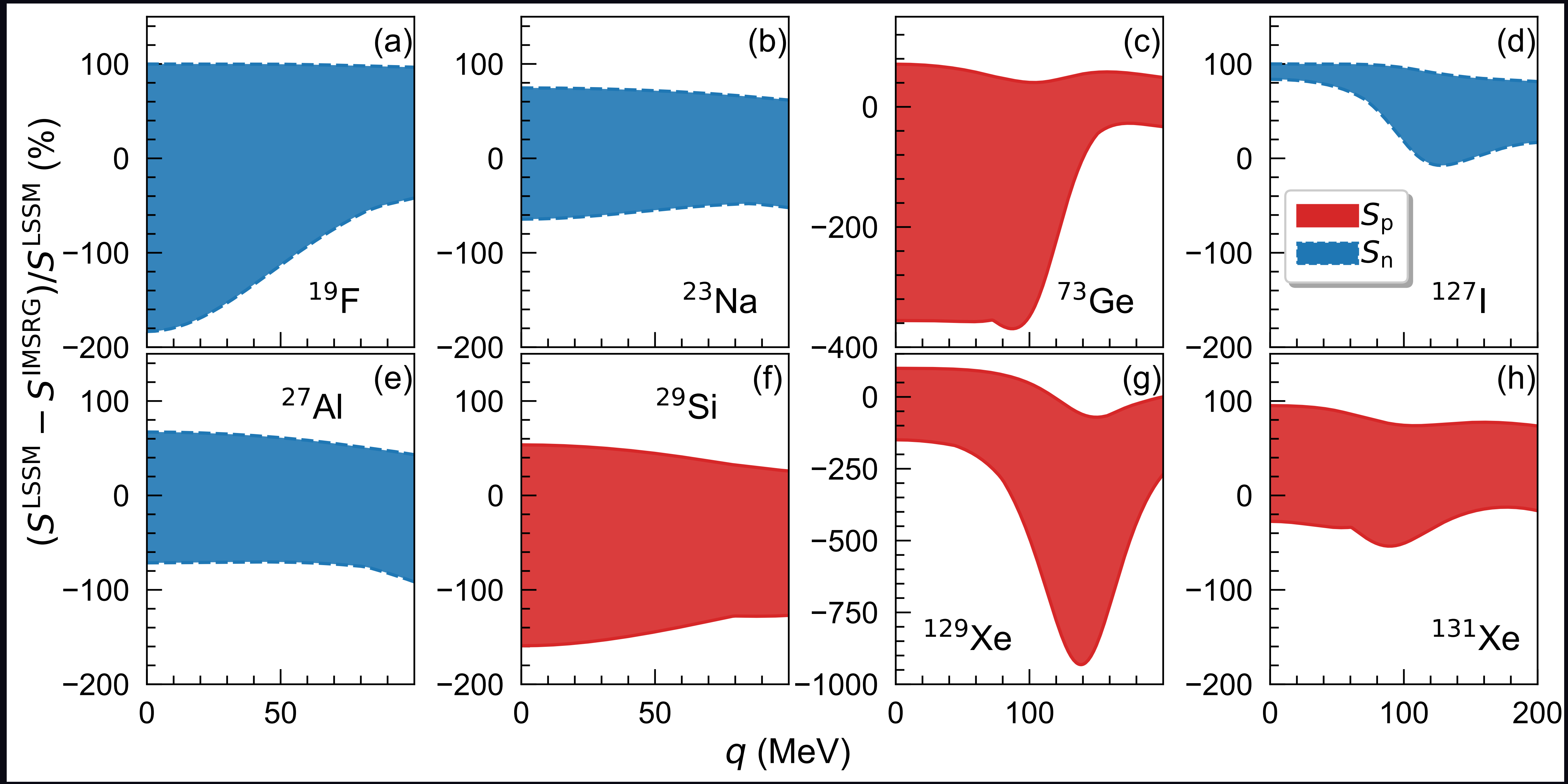
B.S. Hu, et al, Phys. Rev. Lett. 128 (2022) 072502; arXiv: 2109.00193.

Discrepancy between LSSM and VS-IMSRG

Dominant structure factor



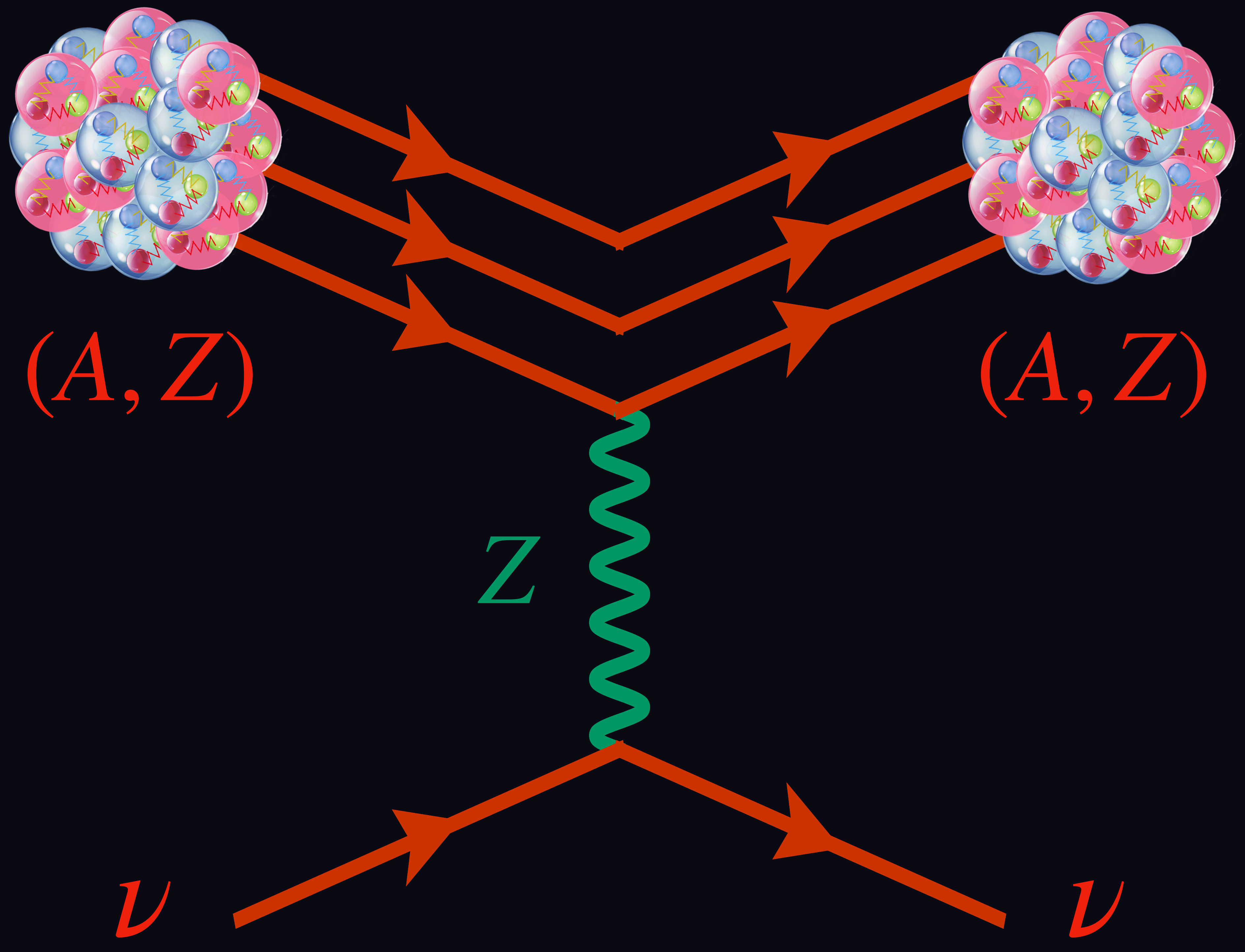
Non-dominant structure factor



Part II

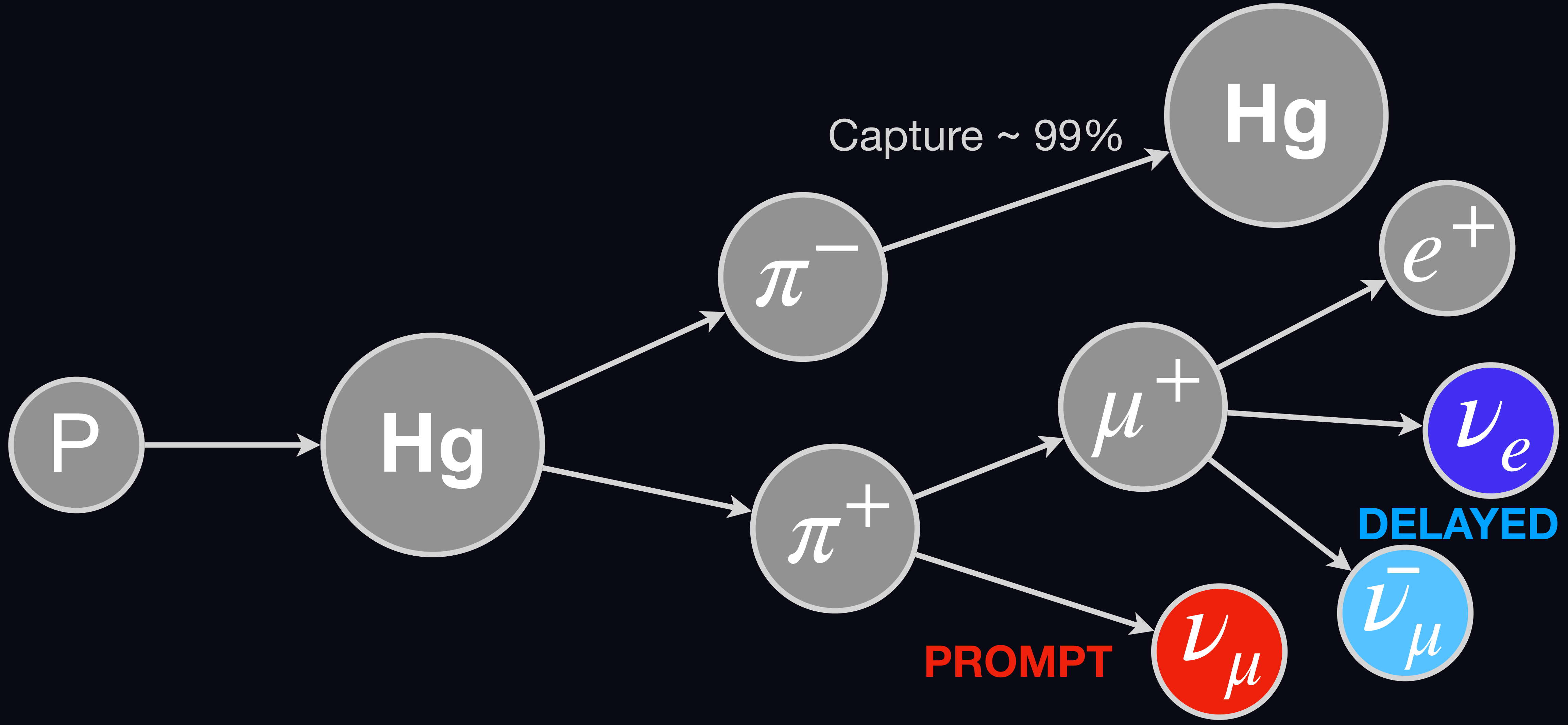
Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)

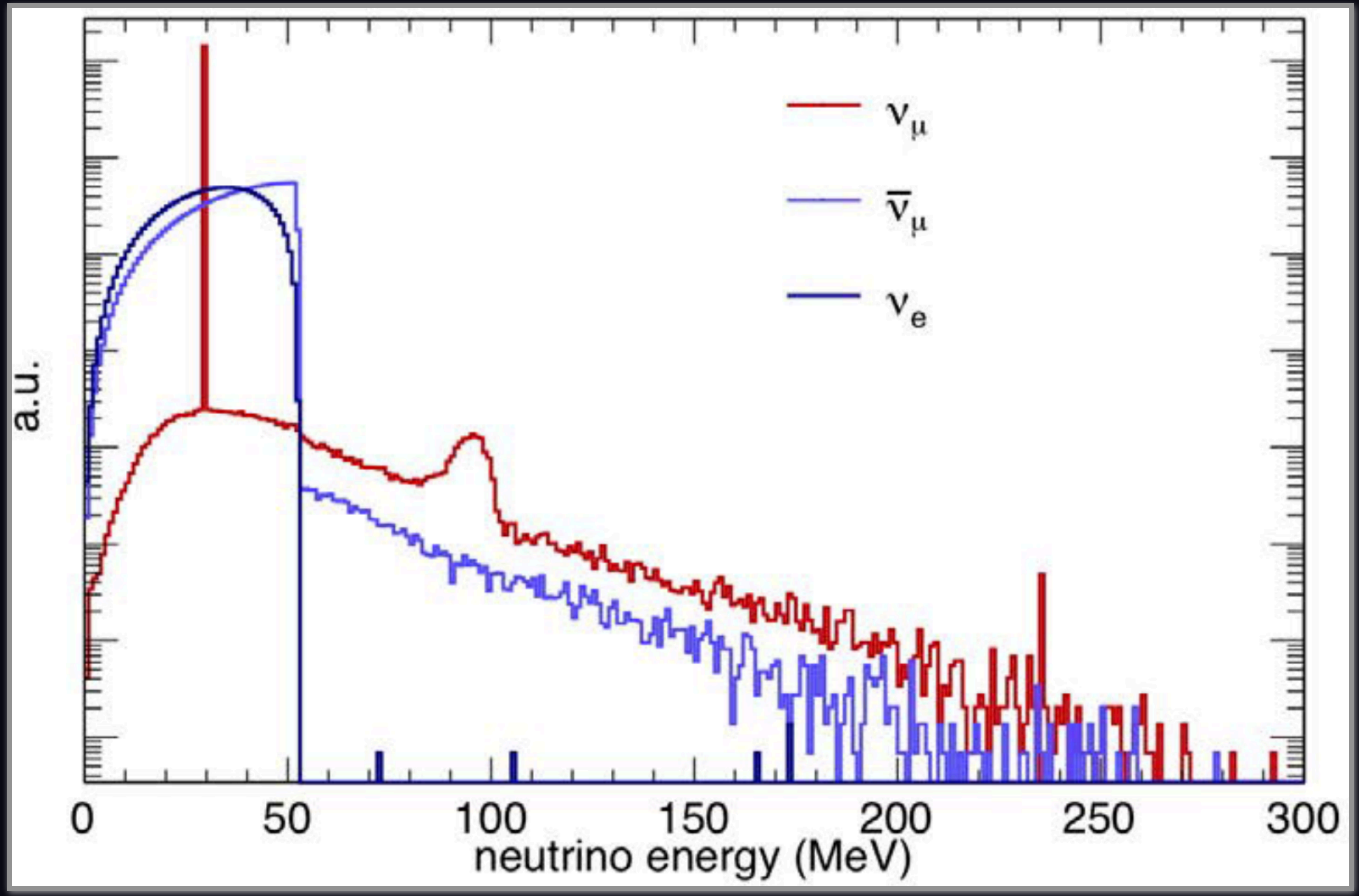
A neutrino interacts a nucleus via exchange of a Z, and the nucleus recoils as a whole

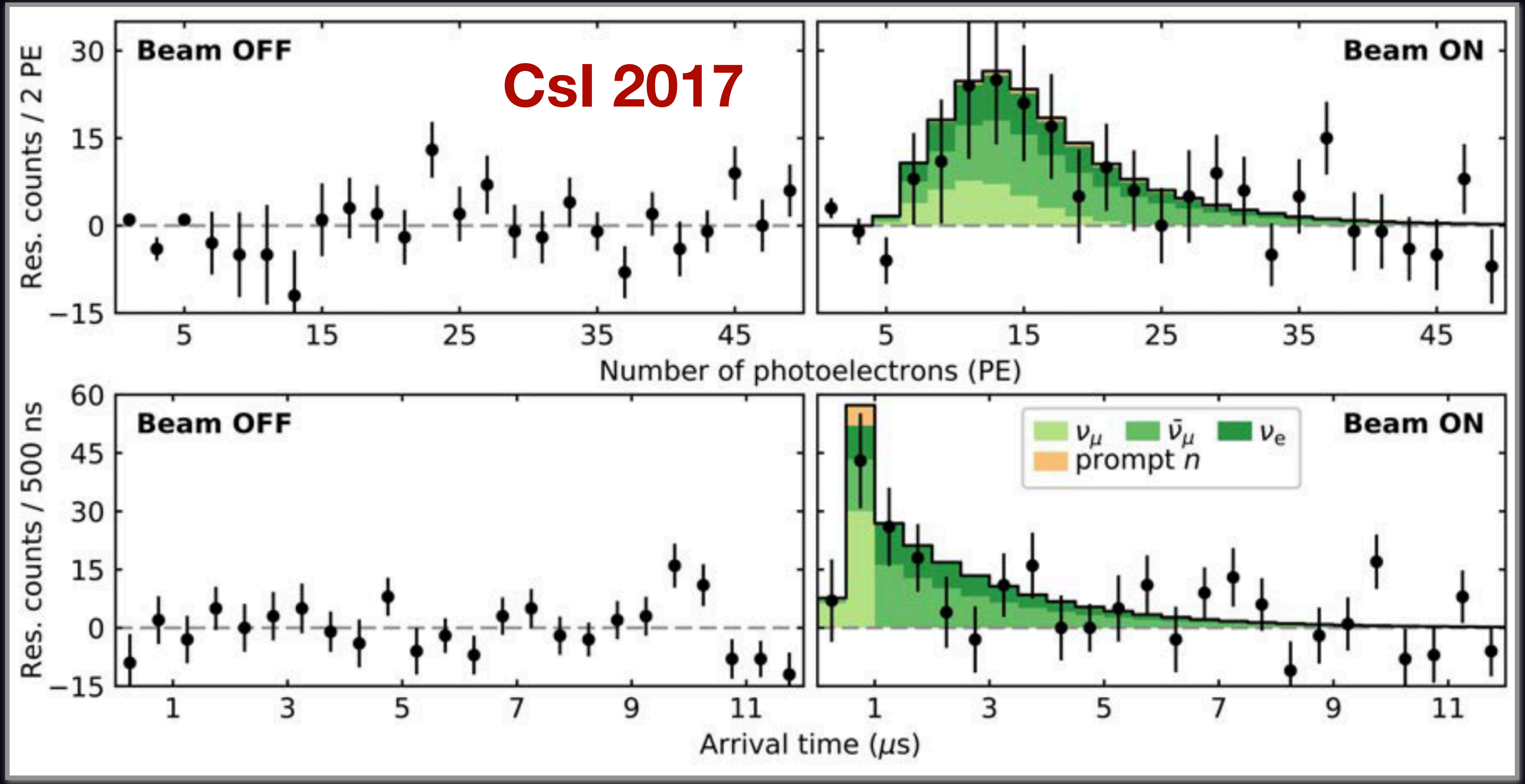


COHERENT experiment

SNS as a neutrino source

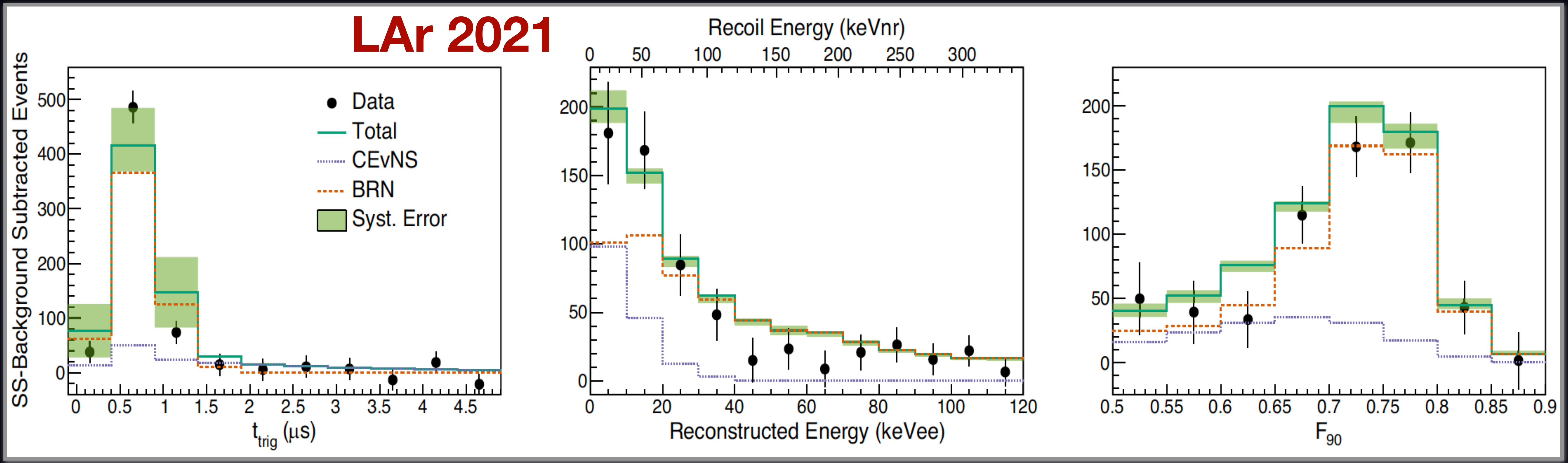




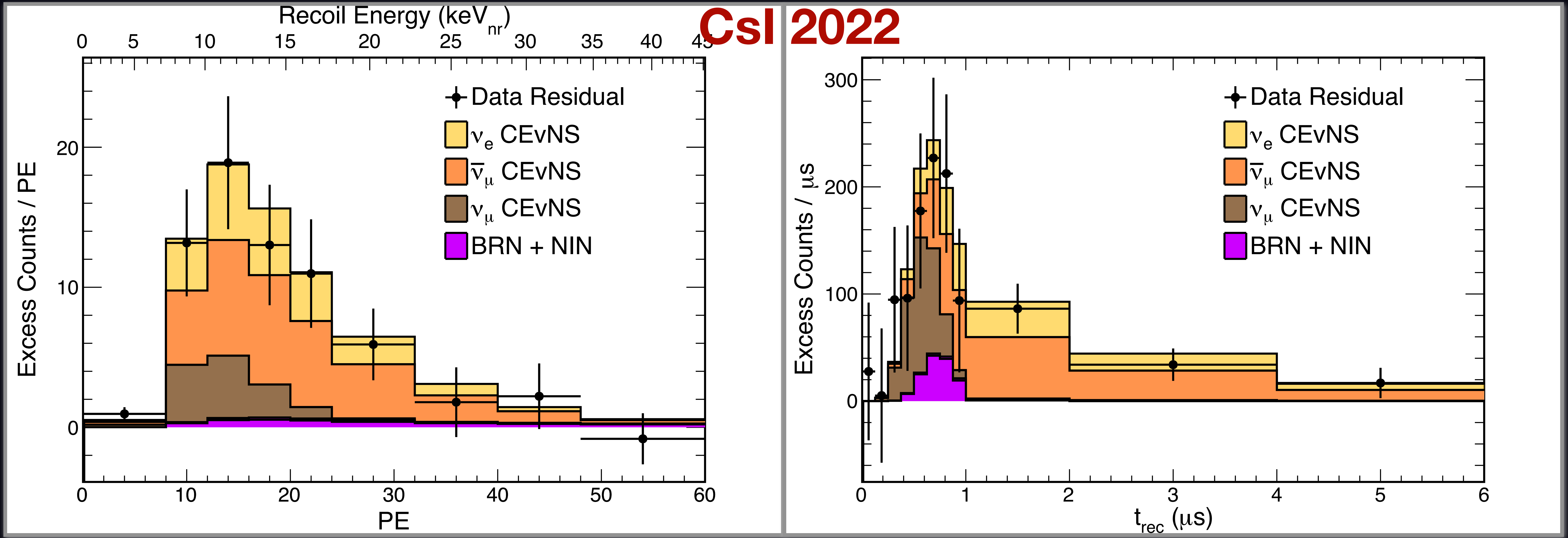


D. Akimov et al. (COHERENT). Science 357, 1123 (2017)

COHERENT experiment



D. Akimov et al. (COHERENT). Phys. Rev. Lett. 126, 012002 (2021)



D. Akimov et al. (COHERENT). Phys. Rev. Lett. 129, 081801 (2022)

Weak mixing angle

Astrophysics

BSM

CEvNS from

natural, accelerator,
reactor neutrinos

Neutrino floor

Nuclear structure

EW precision tests

...

CEvNS differential cross section

$$\frac{d\sigma_A}{dT}(E_\nu, T) = \frac{G_F^2 M_A}{4\pi}\left(1 - \frac{M_A T}{2E_\nu^2} - \frac{T}{E_\nu}\right) Q_w^2 \left| F_w\left(\mathbf{q}^2\right)\right|^2 + \frac{G_F^2 M_A}{4\pi}\left(1 + \frac{M_A T}{2E_\nu^2} - \frac{T}{E_\nu}\right) F_A\left(\mathbf{q}^2\right)$$

$$q = \sqrt{2M_A E_\nu T/(E_\nu - T)} \approx \sqrt{2M_A T}$$

Weak charge

$$Q_w = ZQ_w^p + NQ_w^n$$

$$Q_w^p = 0.0714,\ Q_w^n = -0.9900\ ?$$

$$Q_w^n = -1,\ Q_w^p = 1 - 4\sin^2\theta_W,\ \sin^2\theta_W = 0.23122 \pm 0.00003\,?$$

Radiative corrections ?

Axial-vector form factor F_A

Negligible ?

Nuclear weak form factor F_W

Phenomenological Helm and Klein-Nystrand

$$F_{\text{Helm}}(q^2) = \frac{3j_1\left(qR\right)}{qR} e^{-q^2 s^2/2}$$

$$F_{\text{KN}}(q^2) = \frac{3j_1\left(qR_A\right)}{qR_A} \frac{1}{1 + q^2 a_{kn}^2}$$

Chiral EFT: Systematic expansion of nuclear forces and electroweak currents

$$F_{\mathrm{w}}\left(\mathbf{q}^2\right) = \frac{1}{Q_{\mathrm{w}}}\left\{\left[Q_{\mathrm{w}}^p\left(1-\frac{\langle r_E^2\rangle^p}{6}q^2-\frac{1}{8m_{\mathcal{N}}^2}q^2\right)-Q_{\mathrm{w}}^n\frac{\langle r_E^2\rangle^n+\langle r_{E,s}^2\rangle^N}{6}q^2\right]\mathcal{F}_p^M\left(\mathbf{q}^2\right)\right.$$
$$+\left[Q_{\mathrm{w}}^n\left(1-\frac{\langle r_E^2\rangle^p+\langle r_{E,s}^2\rangle^N}{6}q^2-\frac{1}{8m_{\mathcal{N}}^2}q^2\right)-Q_{\mathrm{w}}^p\frac{\langle r_E^2\rangle^n}{6}q^2\right]\mathcal{F}_n^M\left(\mathbf{q}^2\right)$$
$$+\frac{Q_{\mathrm{w}}^p\left(1+2\kappa^p\right)+2Q_{\mathrm{w}}^n\left(\kappa^n+\kappa_s^N\right)}{4m_{\mathcal{N}}^2}q^2\mathcal{F}_p^{\Phi''}\left(\mathbf{q}^2\right)$$
$$\left.+\frac{Q_{\mathrm{w}}^n\left(1+2\kappa^p+2\kappa_s^N\right)+2Q_{\mathrm{w}}^p\kappa^n}{4m_{\mathcal{N}}^2}q^2\mathcal{F}_n^{\Phi''}\left(\mathbf{q}^2\right)\right\}.$$

$$F_A\left(\mathbf{q}^2\right) = \frac{8\pi}{2J+1}\left[\left(g_A^{s,N}\right)^2 S_{00}^{\mathcal{T}}\left(\mathbf{q}^2\right)-g_A g_A^{s,N}S_{01}^{\mathcal{T}}\left(\mathbf{q}^2\right)+\left(g_A\right)^2 S_{11}^{\mathcal{T}}\left(\mathbf{q}^2\right)\right]$$

$$S_{00}^{\mathcal{T}} = \sum_L\left[\mathcal{F}_+^{\Sigma_L'}\left(\mathbf{q}^2\right)\right]^2,$$

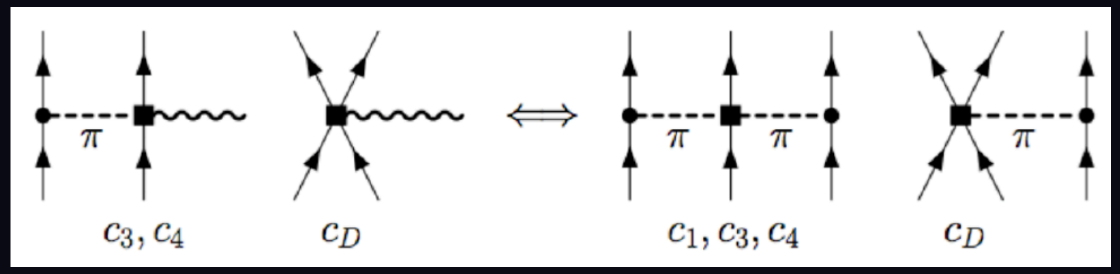
$$S_{11}^{\mathcal{T}} = \sum_L\left[\left[1+\delta'\left(\mathbf{q}^2\right)\right]\mathcal{F}_-^{\Sigma_L'}\left(\mathbf{q}^2\right)\right]^2,$$

$$S_{01}^{\mathcal{T}} = \sum_L 2\left[1+\delta'\left(\mathbf{q}^2\right)\right]\mathcal{F}_+^{\Sigma_L'}\left(\mathbf{q}^2\right)\mathcal{F}_-^{\Sigma_L'}\left(\mathbf{q}^2\right).$$

Details:
M. Hoferichter et al., PRD 102 (2020) 074018
L.A. Ruso et al., arXiv:2203.09030 (2022)

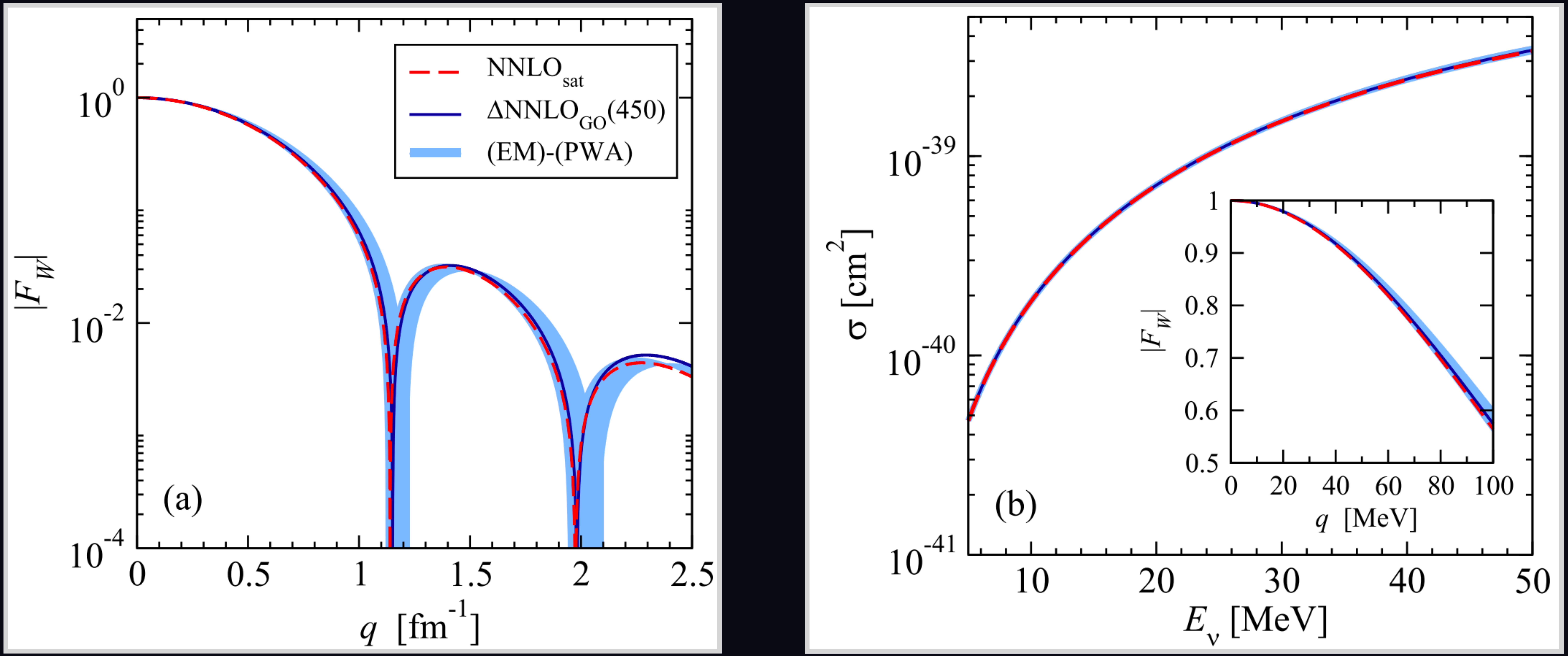
Nuclear response functions

- $\mathcal{F}_\tau^M$: mainly from neutron distribution
- $\mathcal{F}_\tau^{\Phi''}$: spin-orbit correction
- $\mathcal{F}_\tau^{\Sigma'}$: axial-vector contribution; two-body currents important



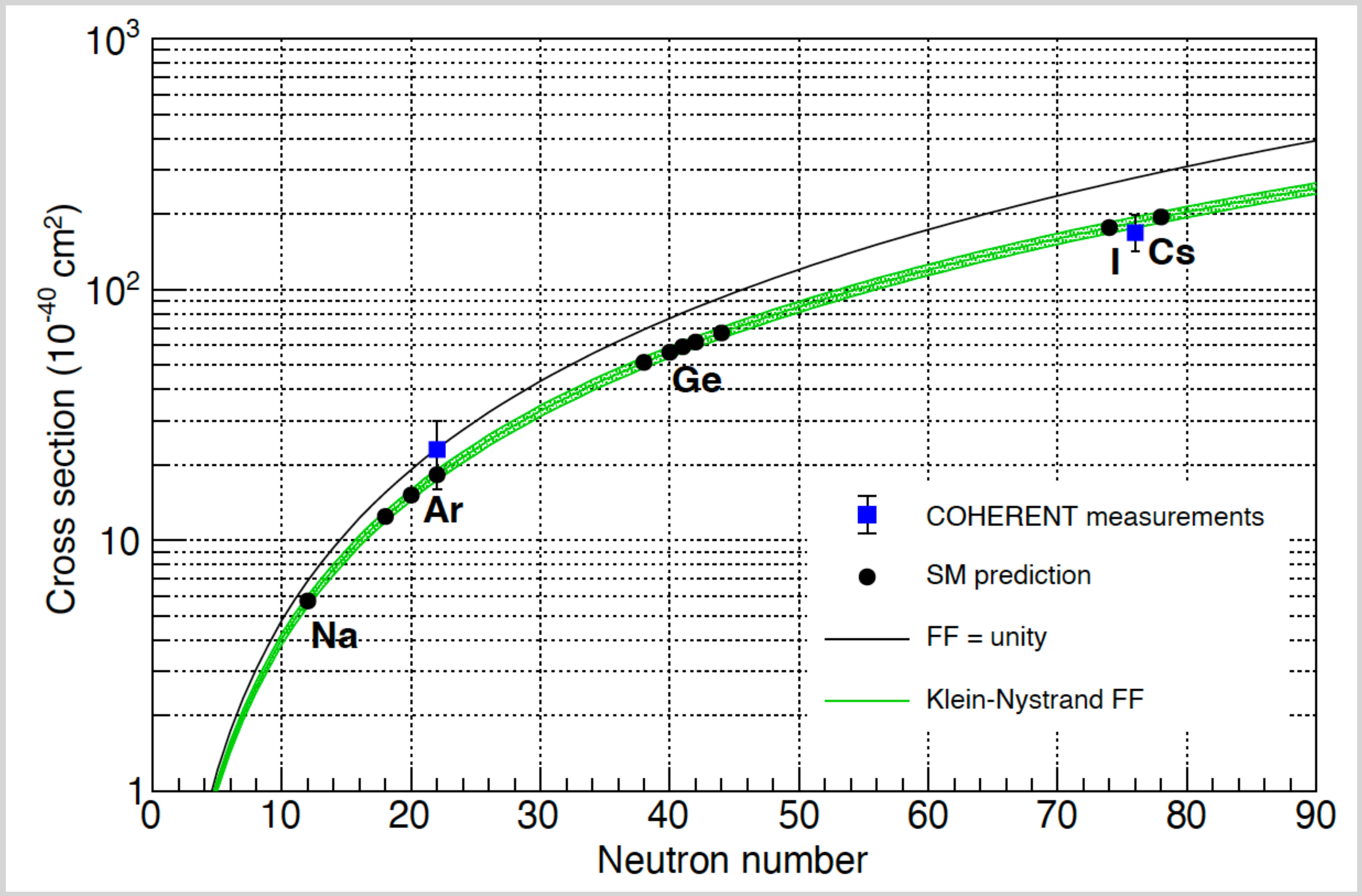
Ab initio form factors ???

Ab initio coupled-cluster calculations of CEvNS in ^{40}Ar



C.G. Payne, S. Bacca, G. Hagen, W.G. Jiang and T. Papenbrock, Phys. Rev. C 100, 061304(R) (2019)

Nuclear target

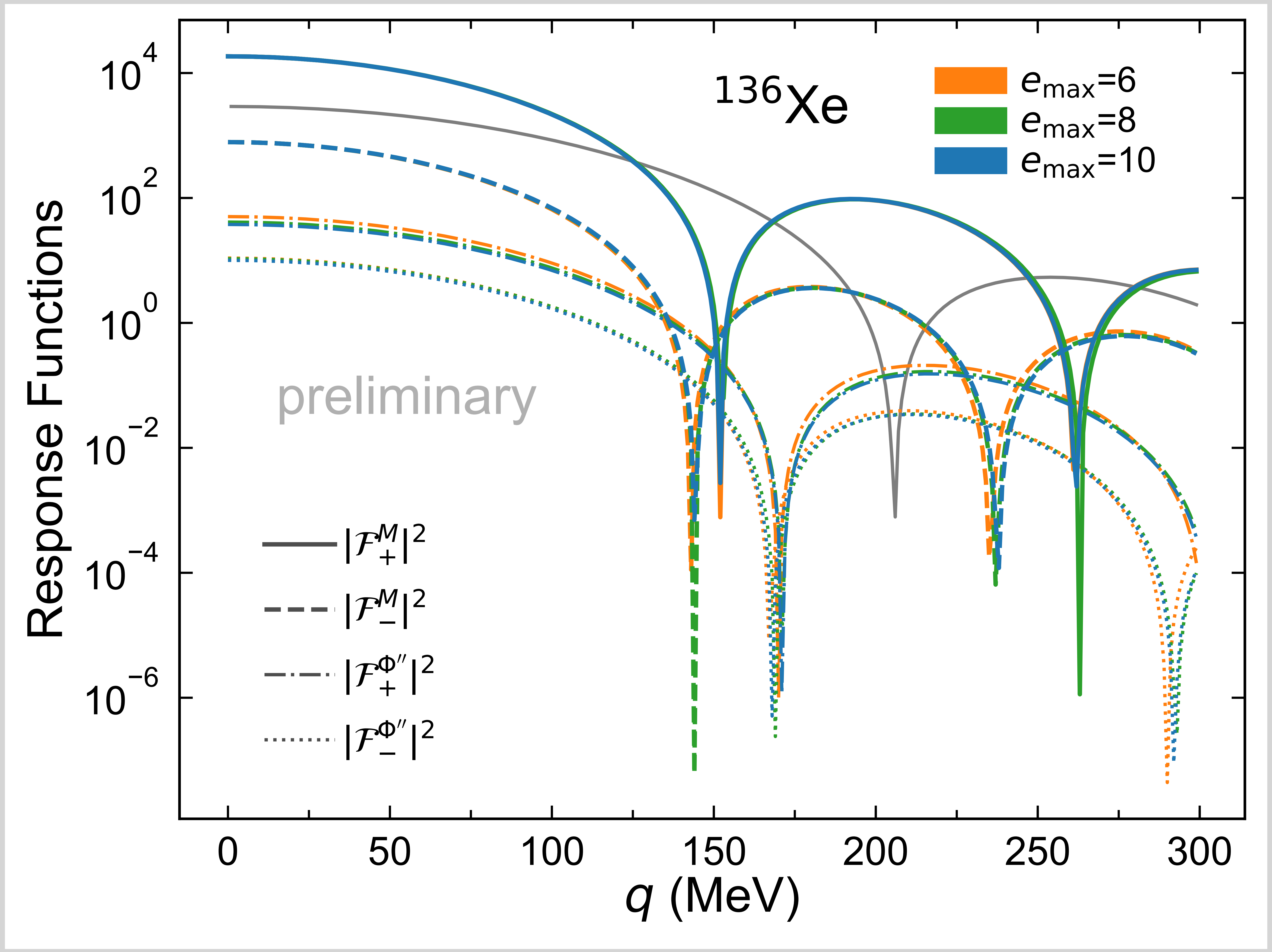


P.S. Barbeau, Yu. Efremenko, K. Scholberg, arXiv:2111.07033 (2021)

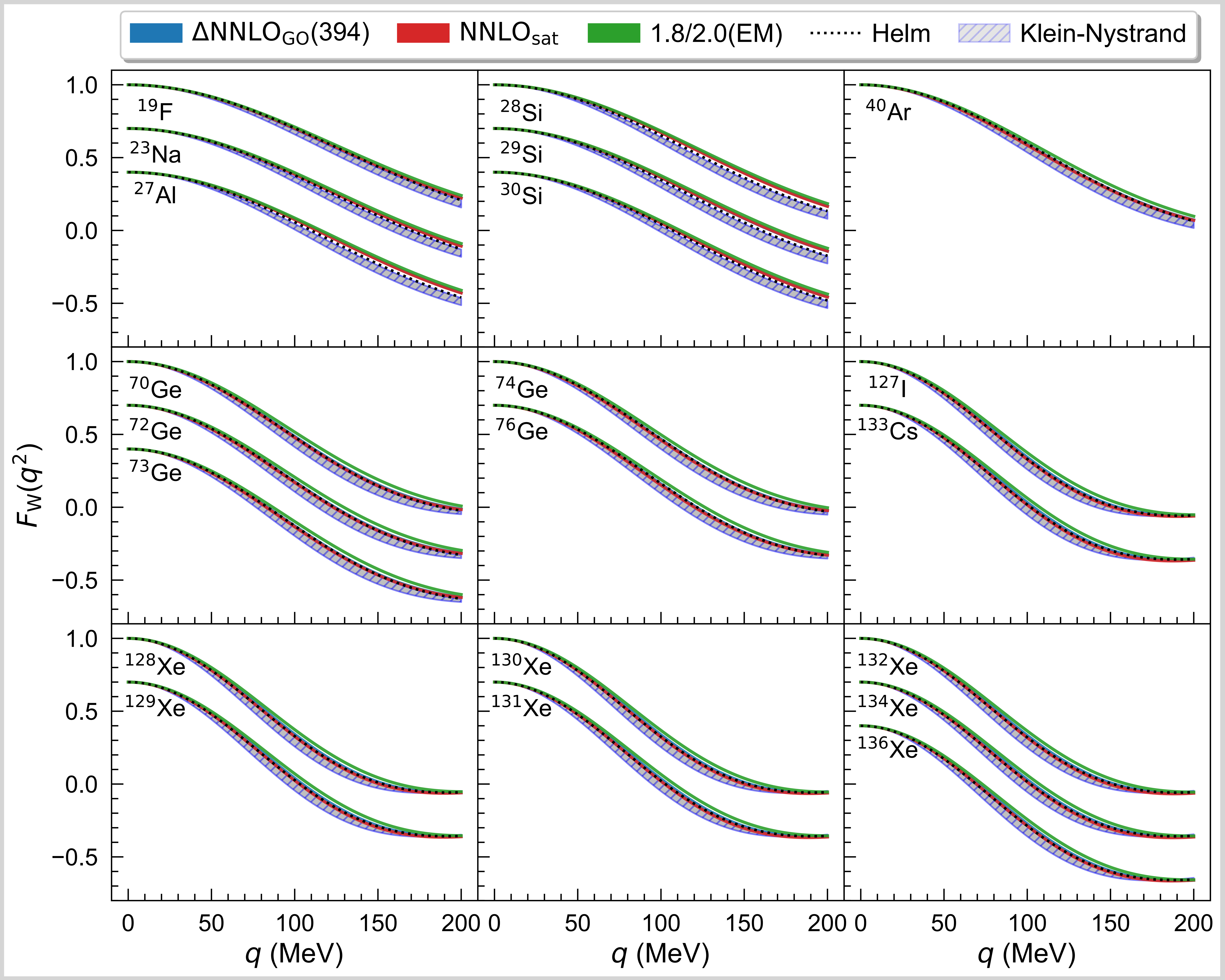
Green band from 3% uncertainty on the nuclear radius in the form factor

Convergence of nuclear response functions within NAT basis

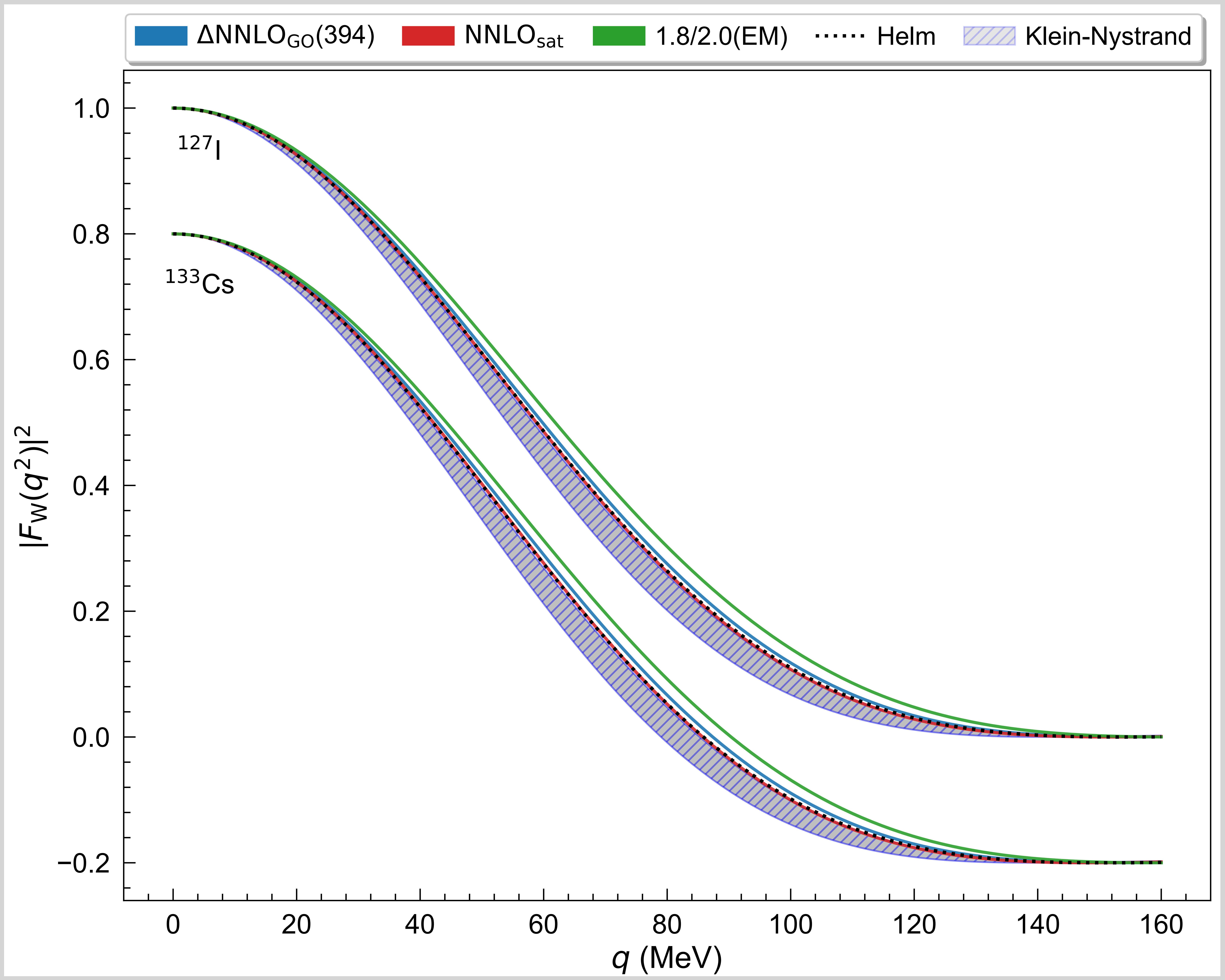
$\mathscr{F}_\tau^M, \mathscr{F}_\tau^{\Phi''}, \mathscr{F}_\tau^{\Sigma'}$



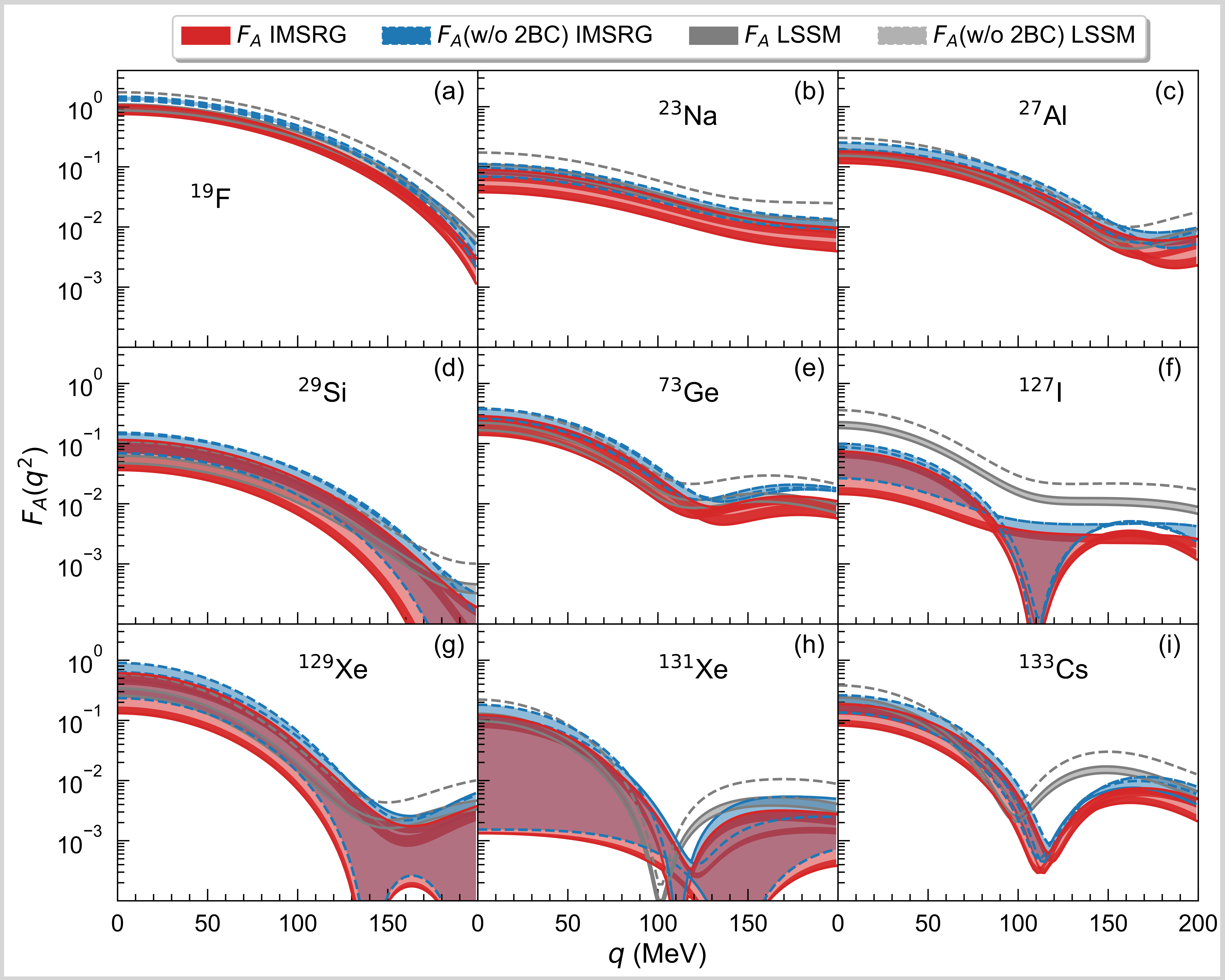
BSH, et al., In preparation (2023)



ΔNNLO_GO(394)
NNLO_sat
1.8/2.0(EM)
Helm
Klein-Nystrand
19F
23Na
27Al
28Si
29Si
30Si
40Ar
70Ge
72Ge
73Ge
74Ge
76Ge
127I
133Cs
128Xe
129Xe
130Xe
131Xe
132Xe
134Xe
136Xe
F_W(q^2)
q (MeV)
1.0
0.5
0.0
−0.5
0
50
100
150
200

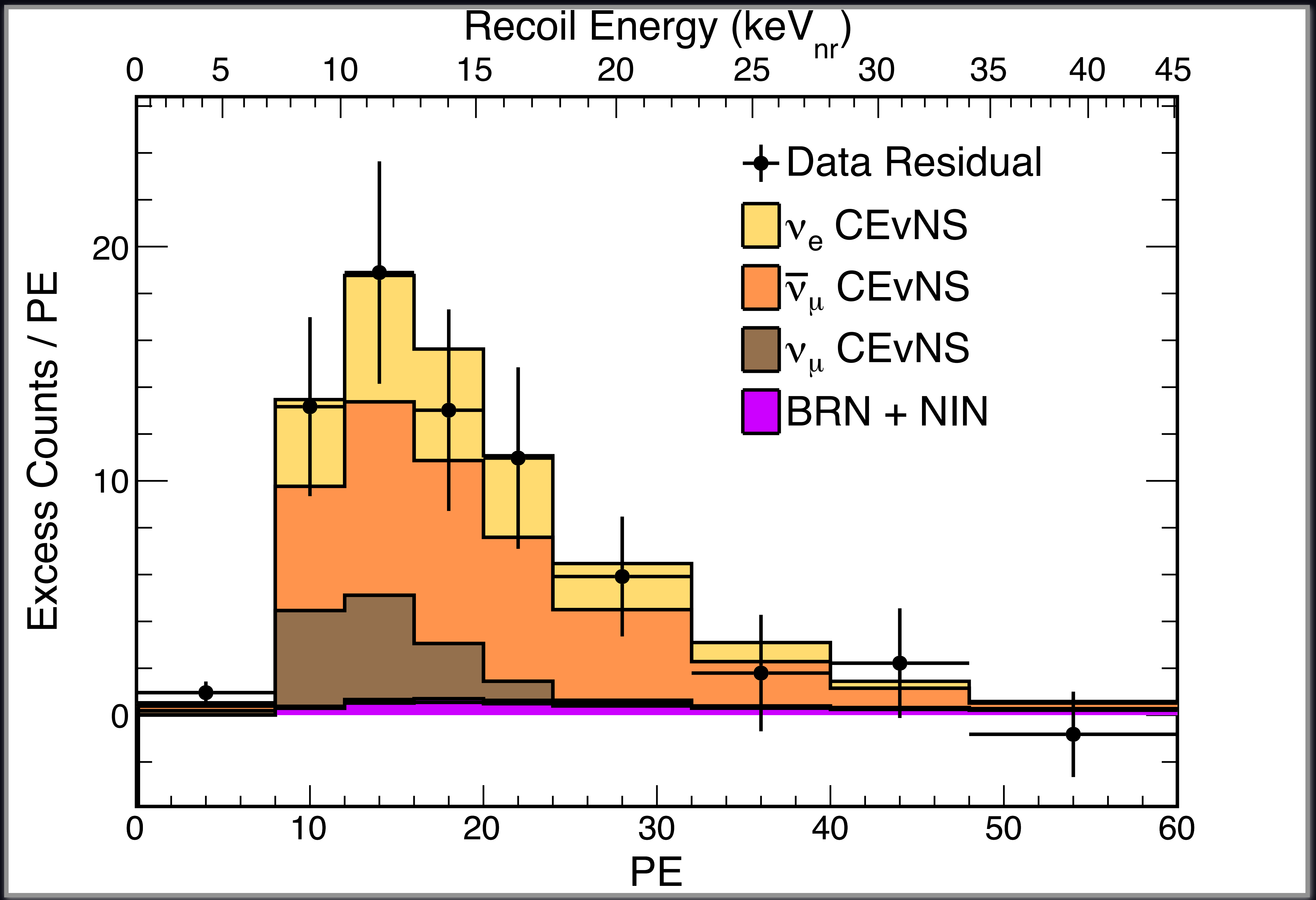


ΔNNLO_GO(394)
NNLO_sat
1.8/2.0(EM)
Helm
Klein-Nystrand
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
|F_W(q^2)|^2
127I
133Cs
0
20
40
60
80
100
120
140
160
q (MeV)



F_A IMSRG
F_A(w/o 2BC) IMSRG
F_A LSSM
F_A(w/o 2BC) LSSM
(a) ^{19}F
(b) ^{23}Na
(c) ^{27}Al
(d) ^{29}Si
(e) ^{73}Ge
(f) ^{127}I
(g) ^{129}Xe
(h) ^{131}Xe
(i) ^{133}Cs
10^{0}
10^{-1}
10^{-2}
10^{-3}
$F_A(q^2)$
0
50
100
150
200
q (MeV)

$$\frac{dR}{dT} = \sum_i \left[N_{\text{target}} X_i \mathcal{N}_\nu \int_{E_\nu^{\min}}^{E_\nu^{\max}} \phi\left(E_\nu\right) \frac{d\sigma_i}{dT} dE_\nu \right]$$



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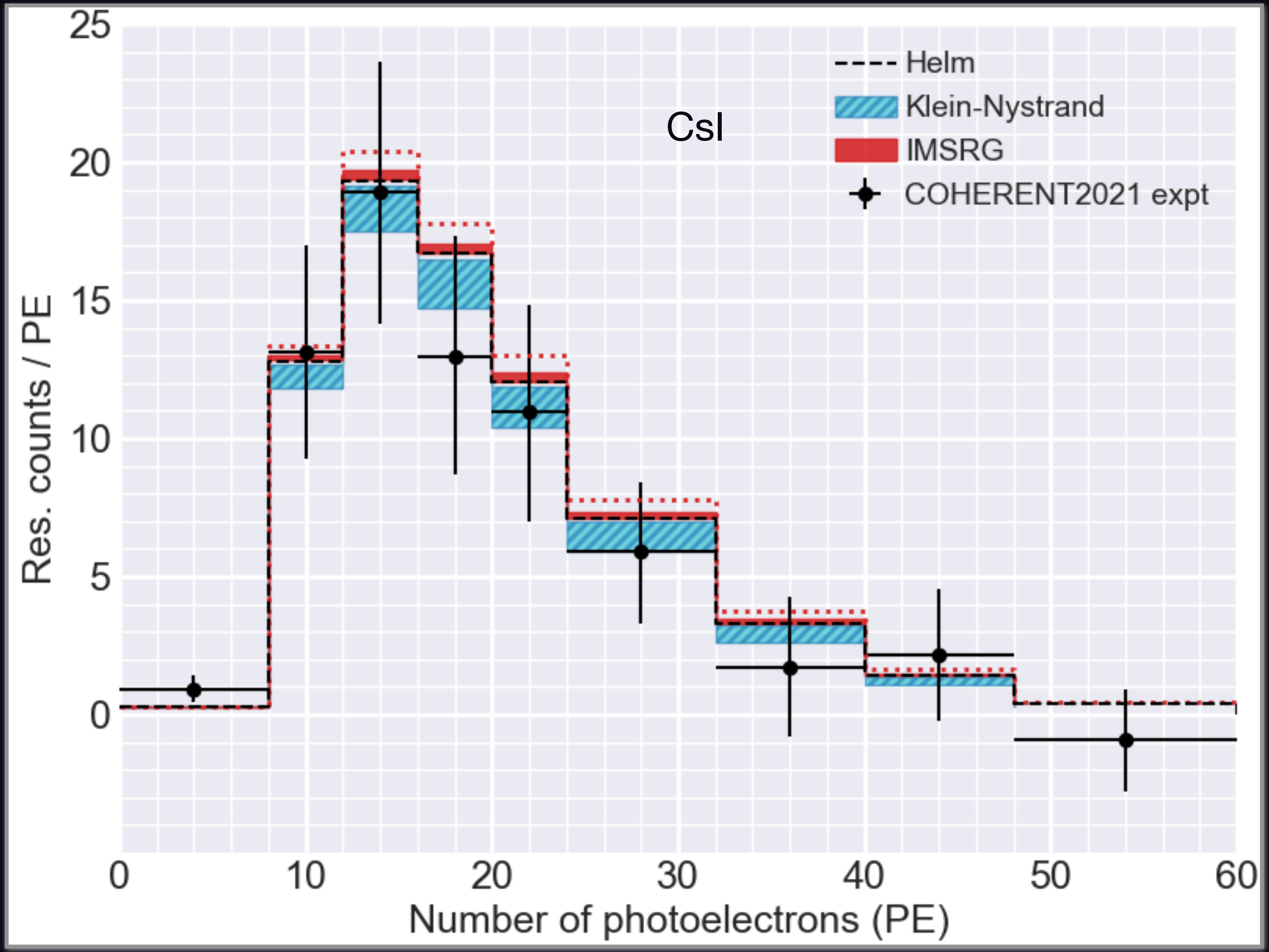
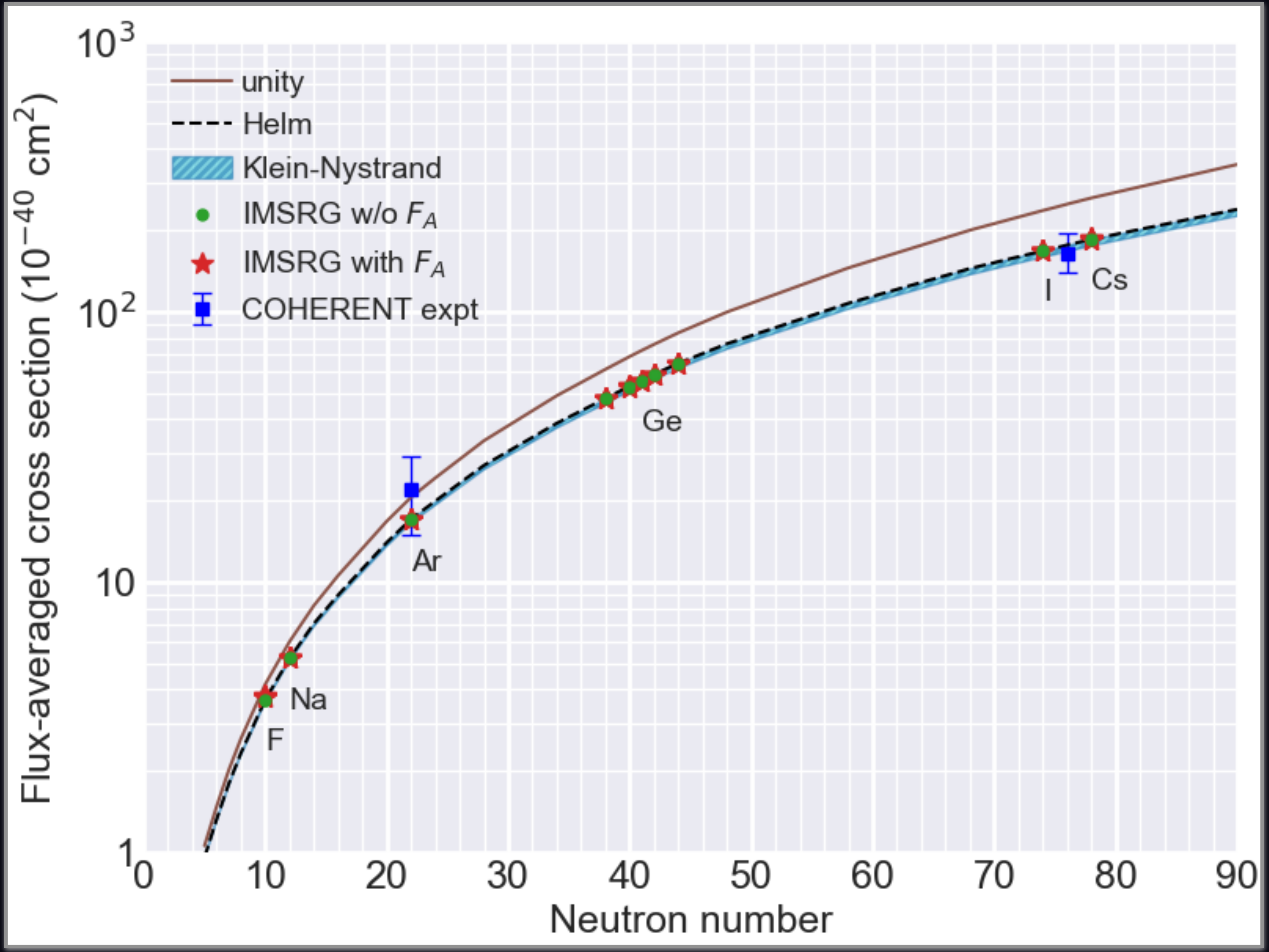


BSH, et al., In preparation (2023)



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- **Helm form factor reproduces ab initio results within NNLOsat well:**

  less than 0.3% in heavy nuclei,
  about 1% in light nuclei

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

$$R^2 = c^2 + \frac{7}{3}\pi^2 a^2 - 5s^2$$

$$c = (1.23A^{1/3} - 0.60)\ \mathrm{fm}$$

$$a = 0.52\ \mathrm{fm},\ s = 0.9\ \mathrm{fm}$$

- **Weak charges:** 1.5% level

$$Q_{\mathrm{w}}^p = 0.0714,\ Q_{\mathrm{w}}^n = -0.9900$$

$$Q_{\mathrm{w}}^n = -1,\ Q_{\mathrm{w}}^p = 1 - 4\sin^2\theta_W \qquad \sin^2\theta_W = 0.23122 \pm 0.00003$$

- **Spin-orbit current** $\mathcal{F}_{\tau}^{\Phi''}$ **:**

  less than 10^(-6)%

- **Axial-vector form factor F_A:**

  3%(^{19}F), 0.1%(^{23}Na), 0.03%(^{73}Ge),
  less than 0.007%(^{127}I and ^{133}Cs)

Summary

VS-IMSRG

Ab initio structure factors/form factors
for ^{19}F, ^{23}Na, ^{27}Al, Si, ^{40}Ar, Ge, ^{127}I, ^{133}Cs, Xe

VS-IMSRG: from light to heavy nuclei
Chiral EFT 1b + 2b currents

Spin-independent WIMP scattering
Inelastic scattering

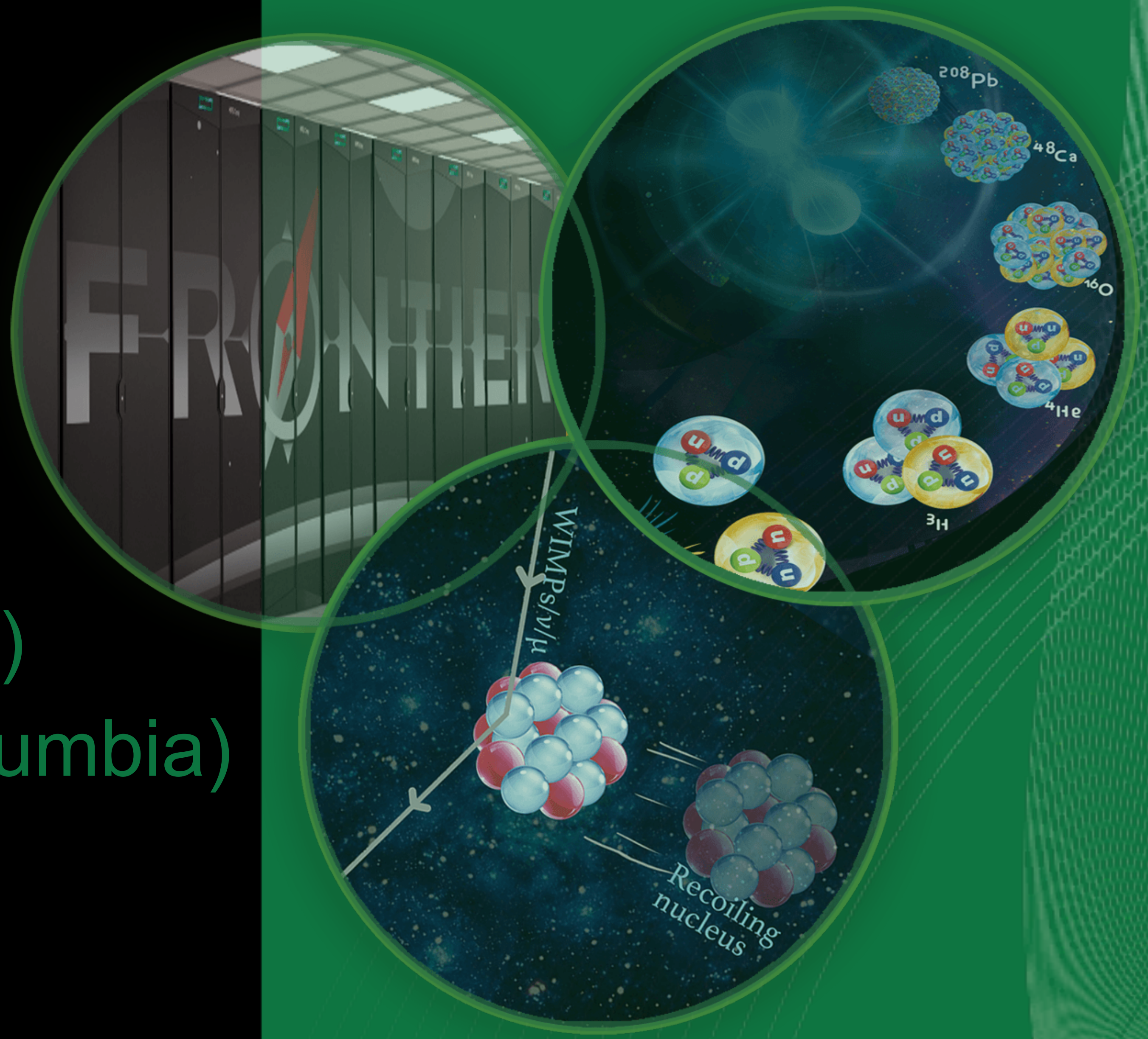
IMSRG gives converged calculation in heavy nuclei

Collaborators:

Gustav Jansen (ORNL)
Gaute Hagen (ORNL and UT)
Thomas Papenbrock (ORNL and UT)
Zhonghao Sun (ORNL)
Bijaya Acharya (ORNL)
Tor Djärv (ORNL)

Jason Holt (TRIUMF)
Takayuki Miyagi (TU Darmstadt)
Ragnar Stroberg (University of Notre Dame)
Mathieu Bruneault (University of British Columbia)

Bhaskar Dutta (Texas A&M University)
Jayden Newstead (University of Melbourne)
Wei-Chih Huang (Texas A&M University)



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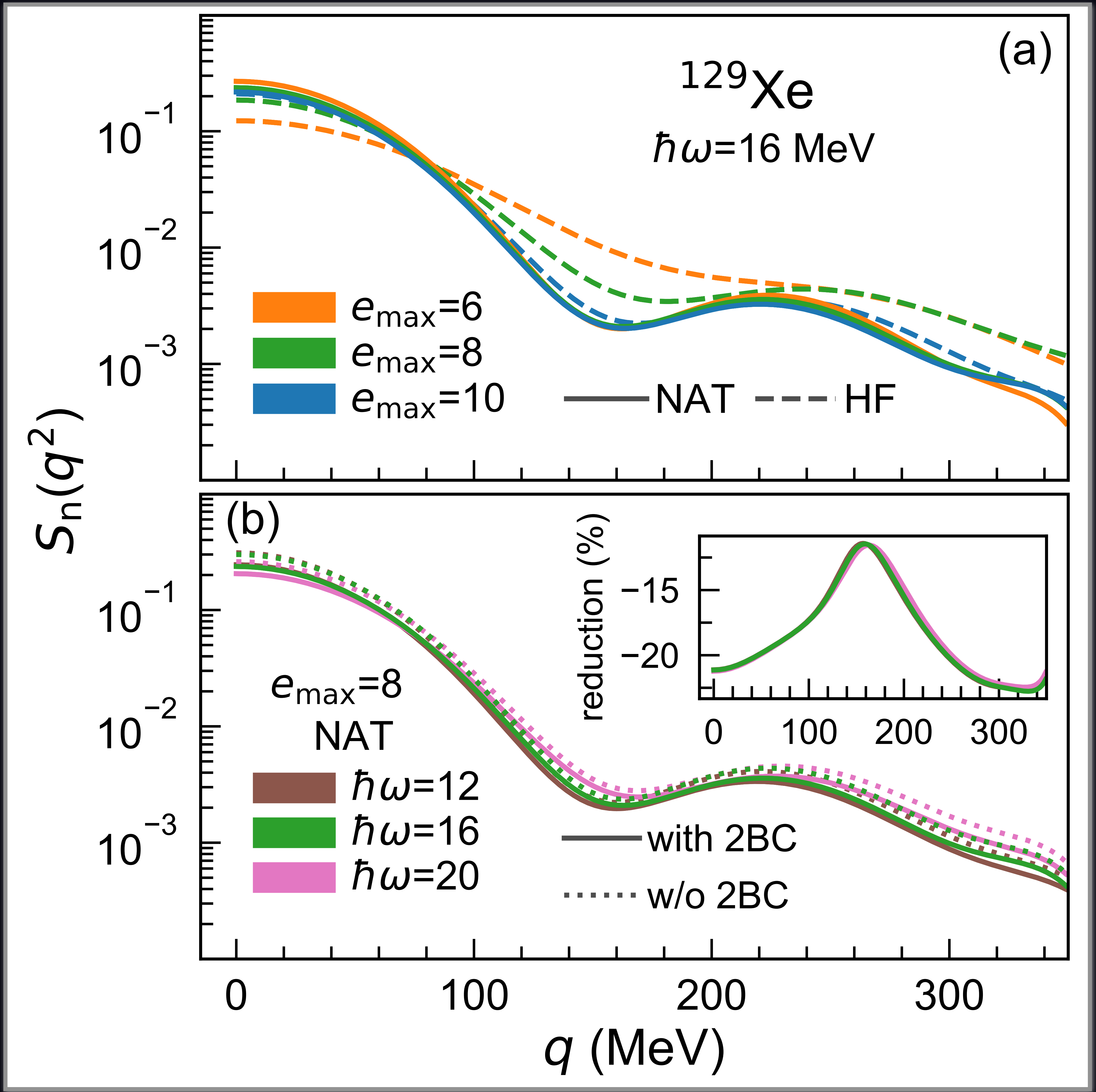
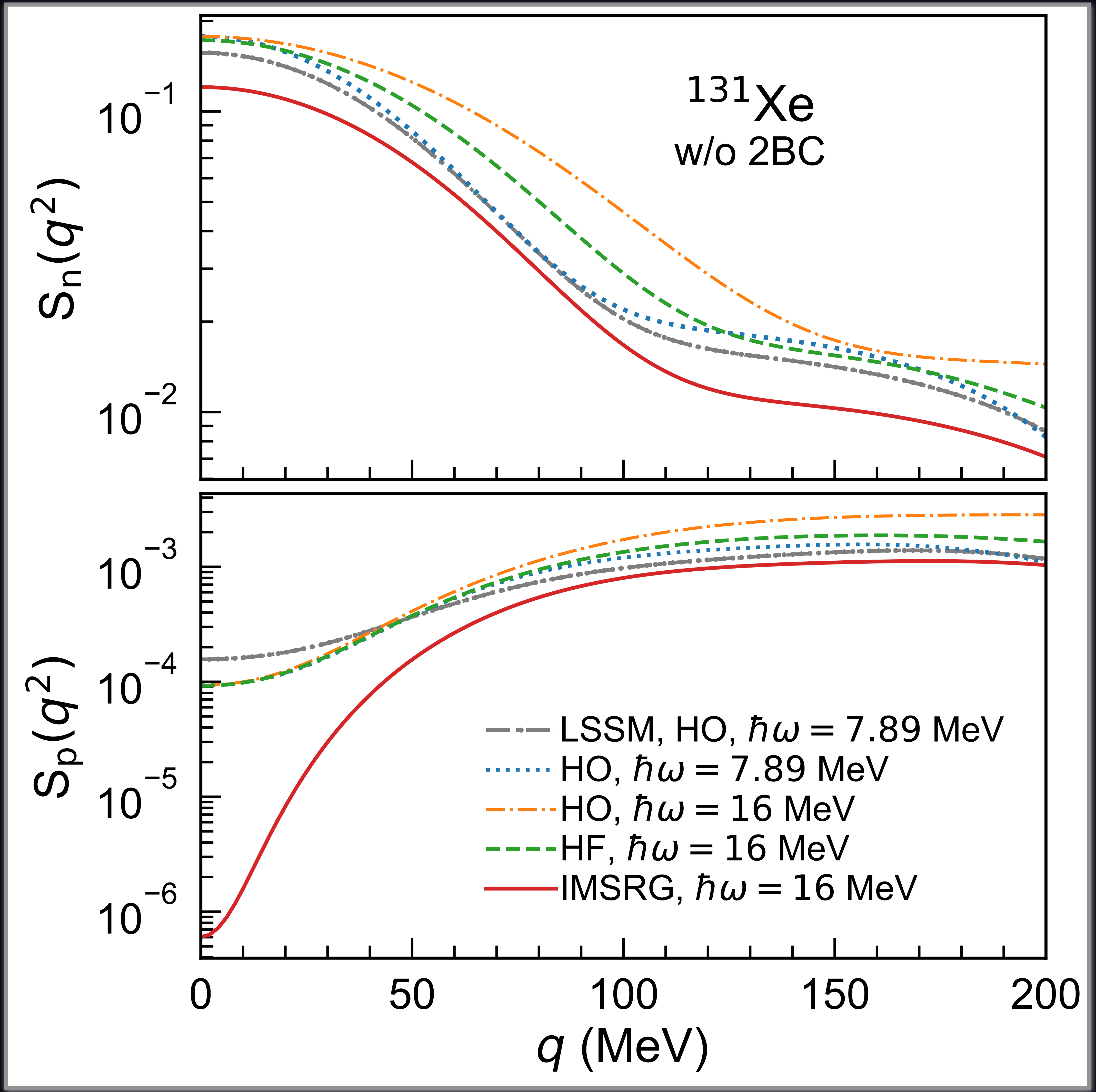
Thank you !

Oak Ridge National Laboratory

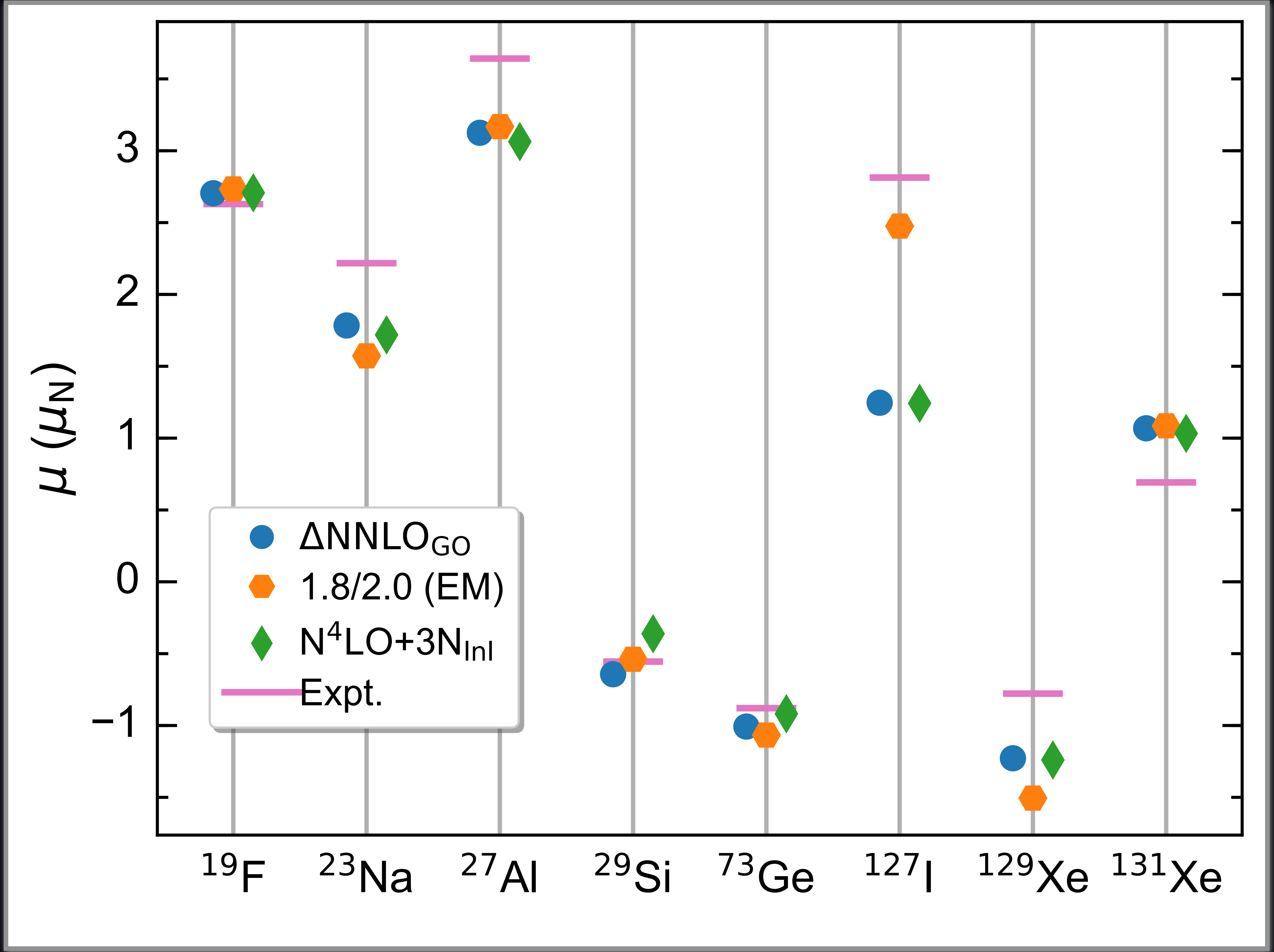


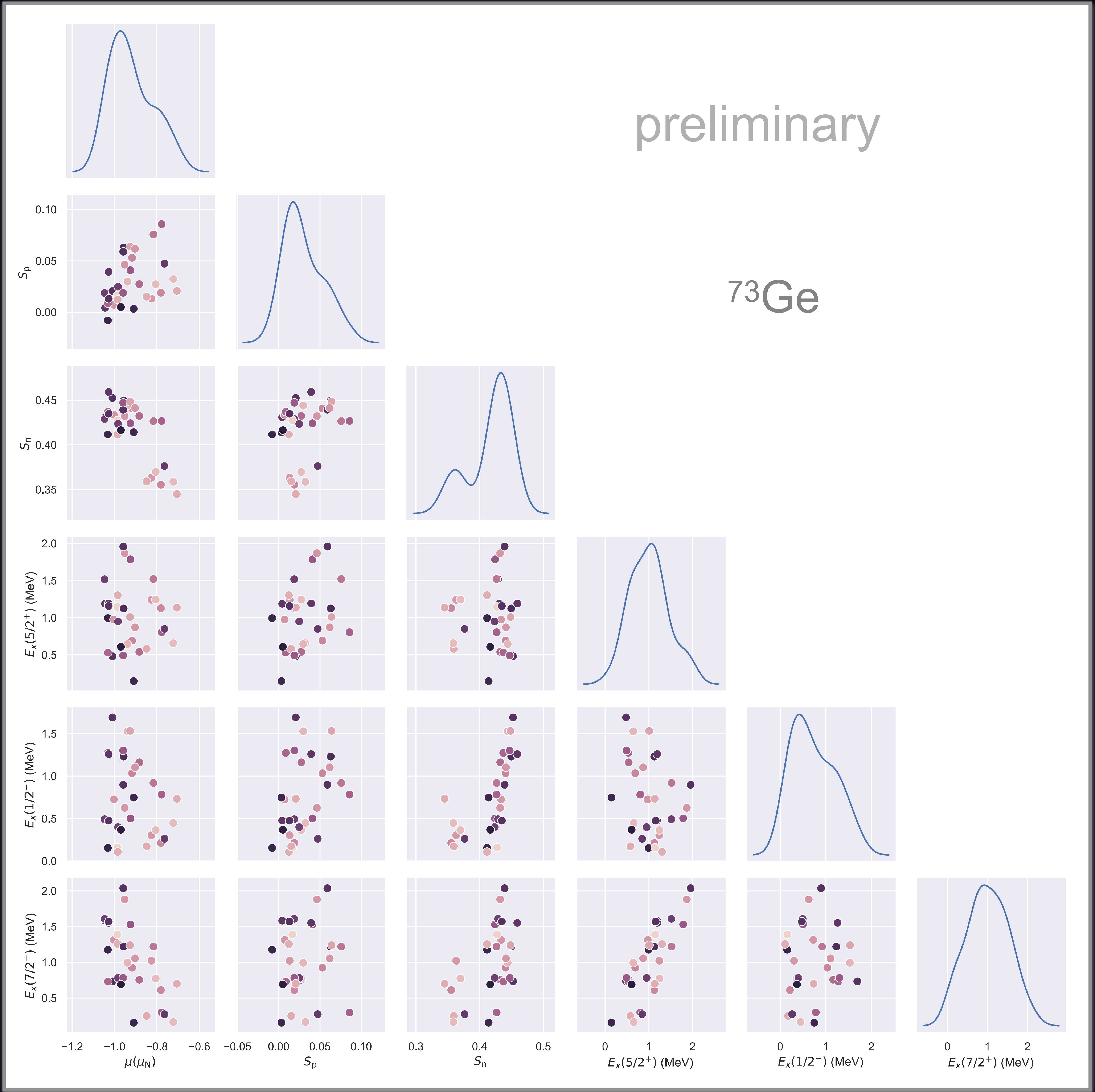
(a)
^{129}Xe
$\hbar\omega$=16 MeV
e_{max}=6
e_{max}=8
e_{max}=10
NAT
HF
(b)
e_{max}=8
NAT
$\hbar\omega$=12
$\hbar\omega$=16
$\hbar\omega$=20
with 2BC
w/o 2BC
reduction (%)
$S_n(q^2)$
q (MeV)



^{131}Xe
w/o 2BC
$S_n(q^2)$
$S_p(q^2)$
LSSM, HO, $\hbar\omega$ = 7.89 MeV
HO, $\hbar\omega$ = 7.89 MeV
HO, $\hbar\omega$ = 16 MeV
HF, $\hbar\omega$ = 16 MeV
IMSRG, $\hbar\omega$ = 16 MeV
q (MeV)

Magnetic dipole moments





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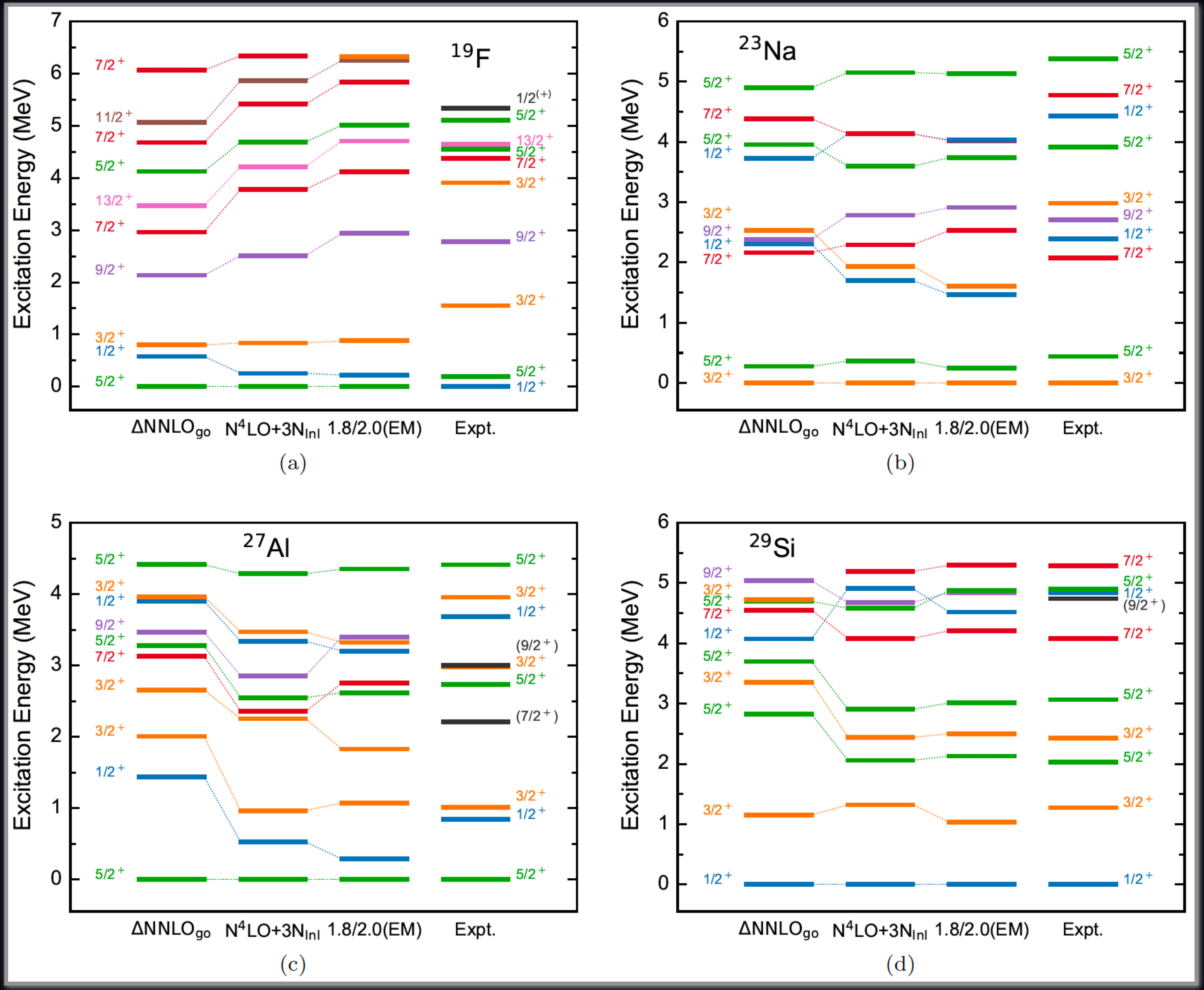
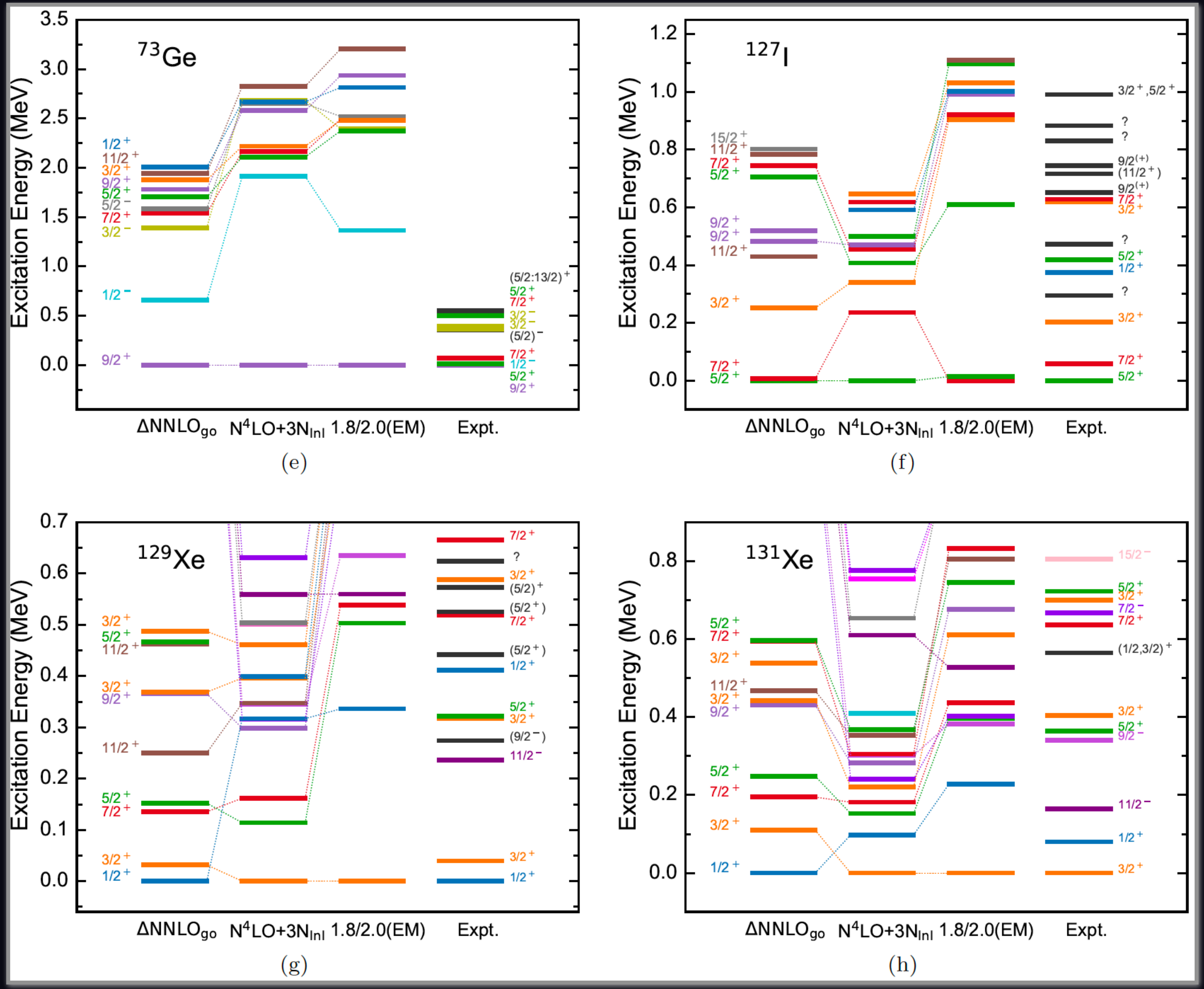
Spectra from VS-IMSRG within NAT





ħw=16 MeV, E3max=22