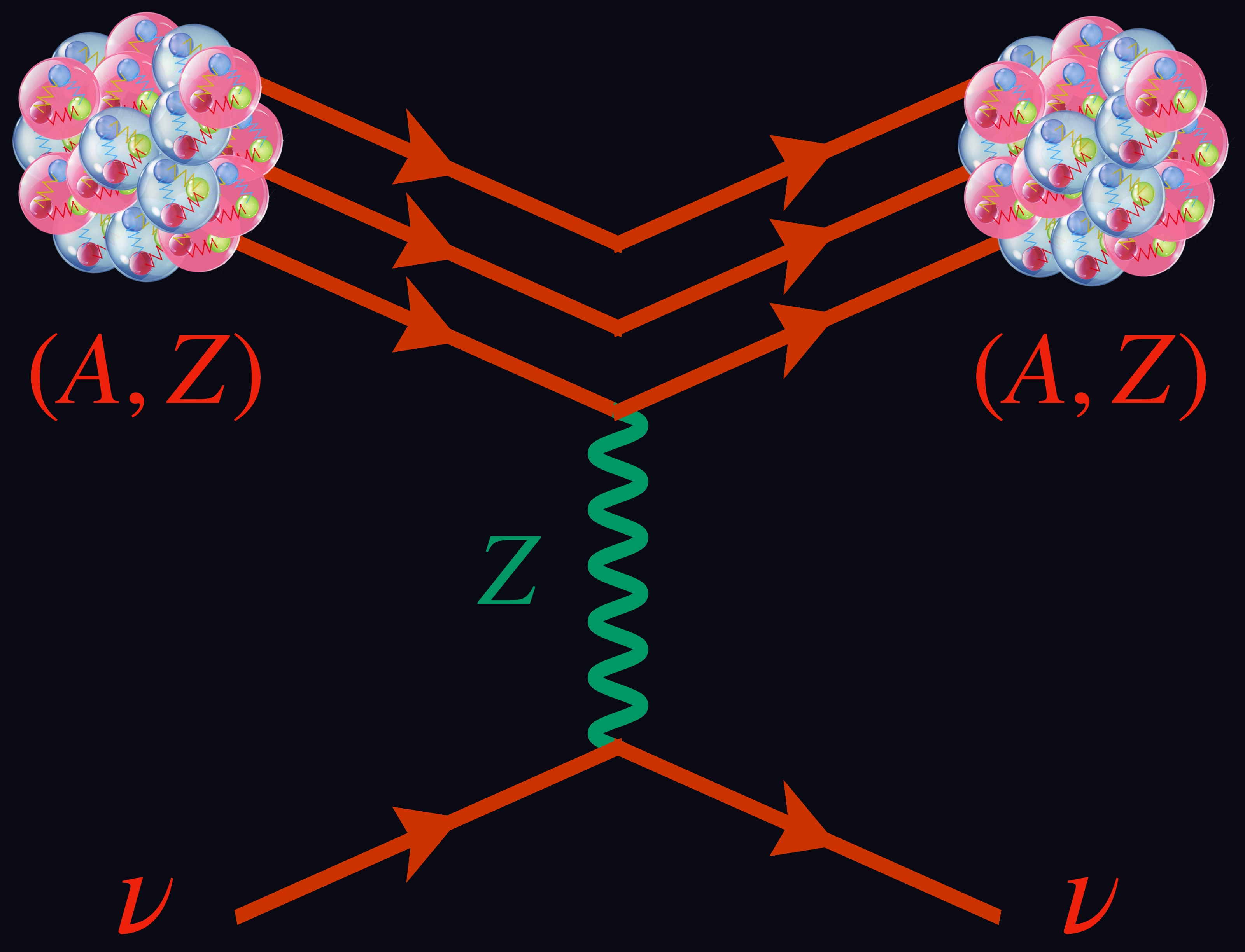
Ab-initio Form Factors for Coherent Elastic Neutrino-Nucleus Scattering



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May 26, 2022 @ MITP (virtual)

Outline

Introduction to CEvNS

VS-IMSRG calculation for CEvNS
(Chiral EFT: NN+3N interactions, 1b + 2b currents)

Outlook: BSM constrains

Weak mixing angle

Astrophysics

BSM

CEvNS from

natural, accelerator,
reactor neutrinos

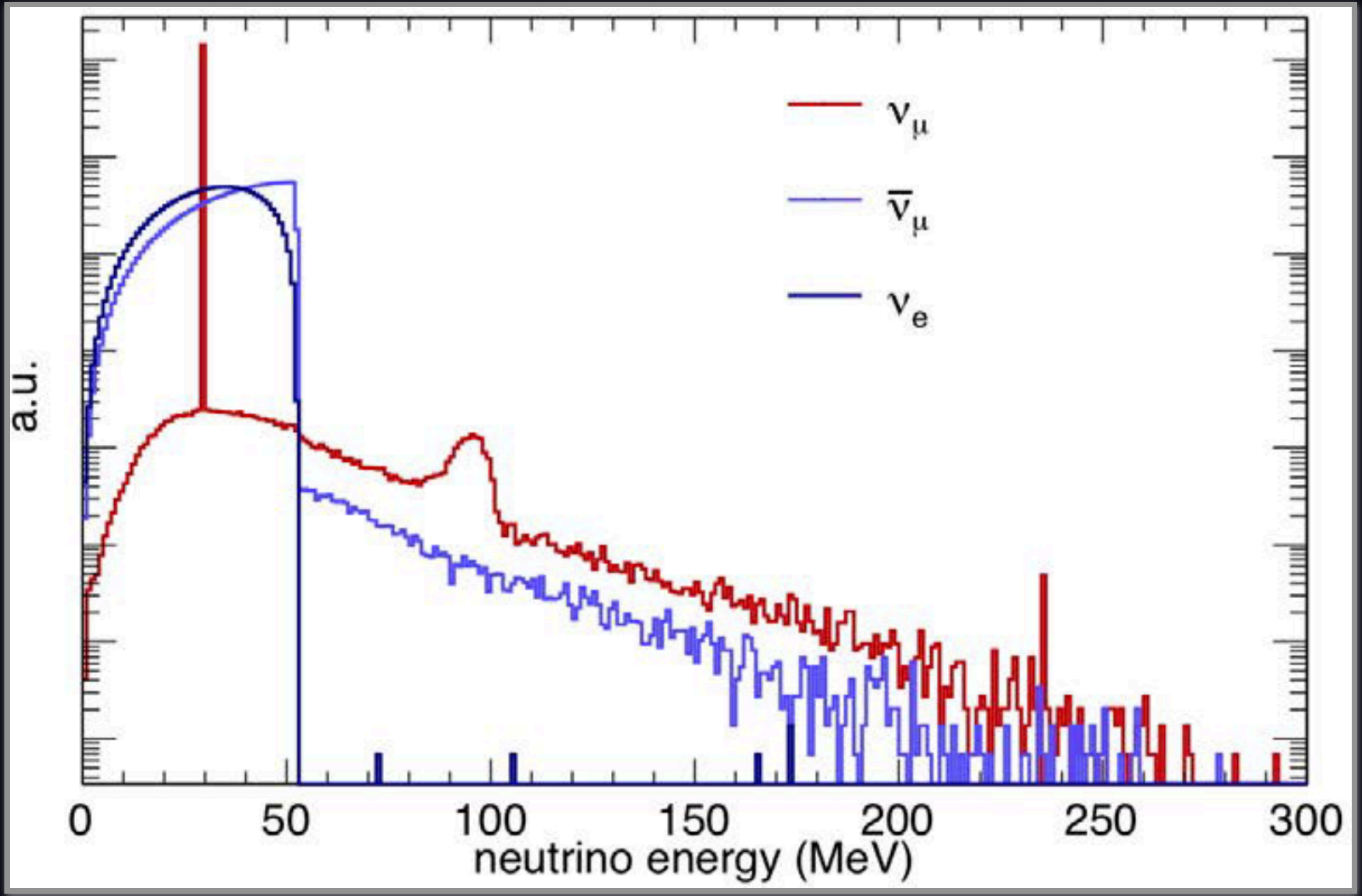
Neutrino floor

Nuclear structure

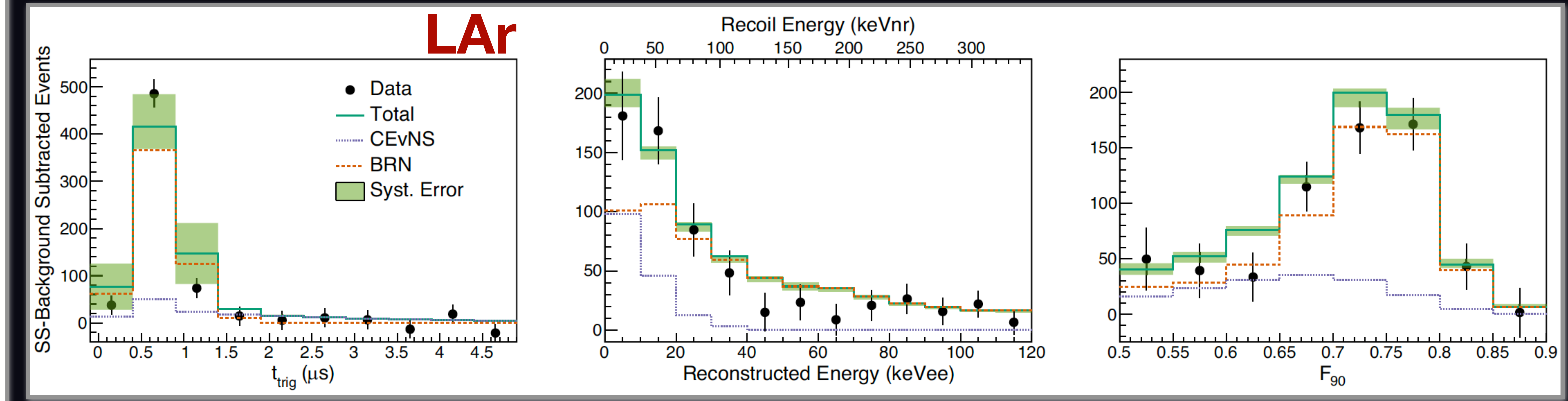
EW precision tests

…

COHERENT experiment



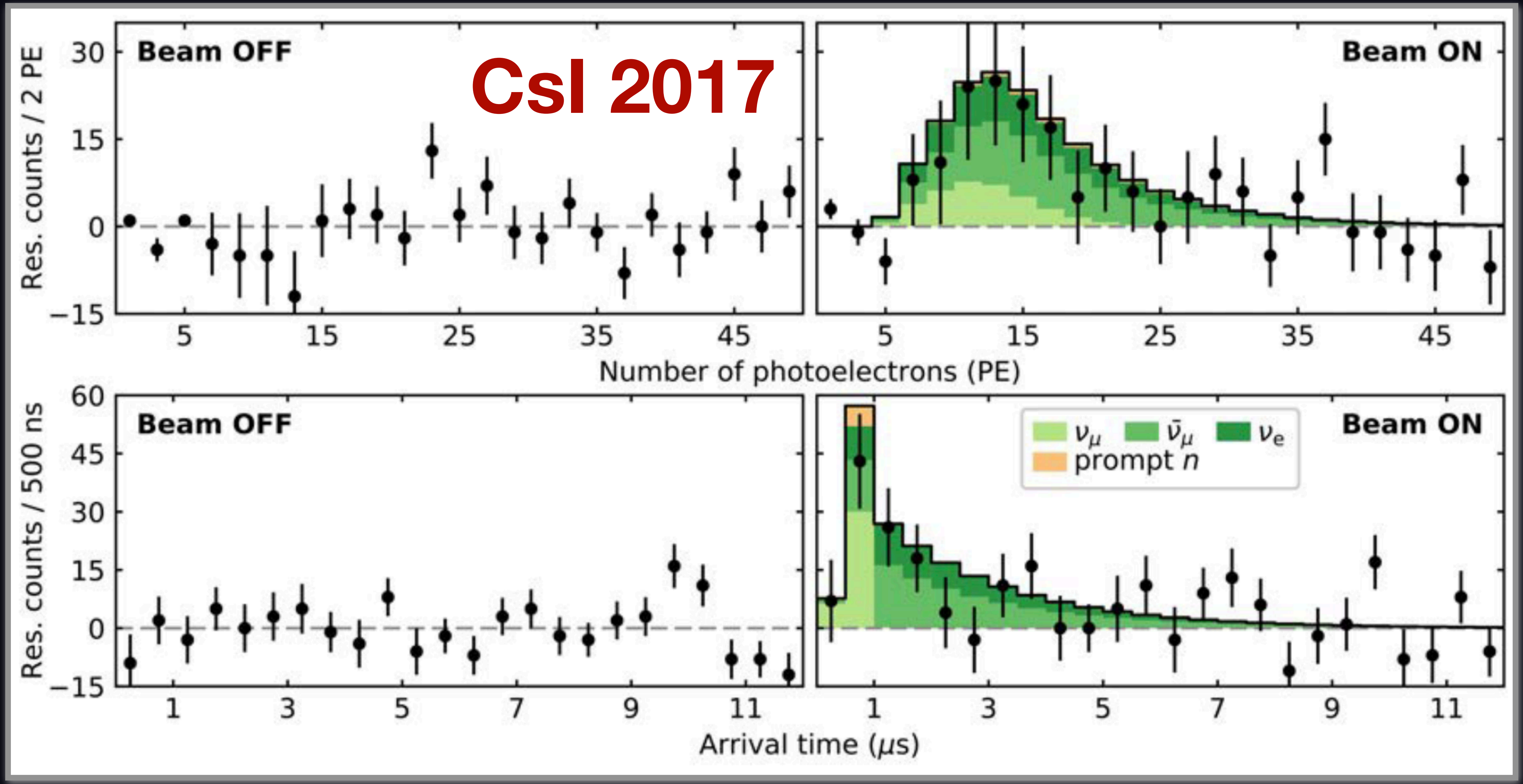
D. Akimov et al. (COHERENT). Science 357 (2017) 1123

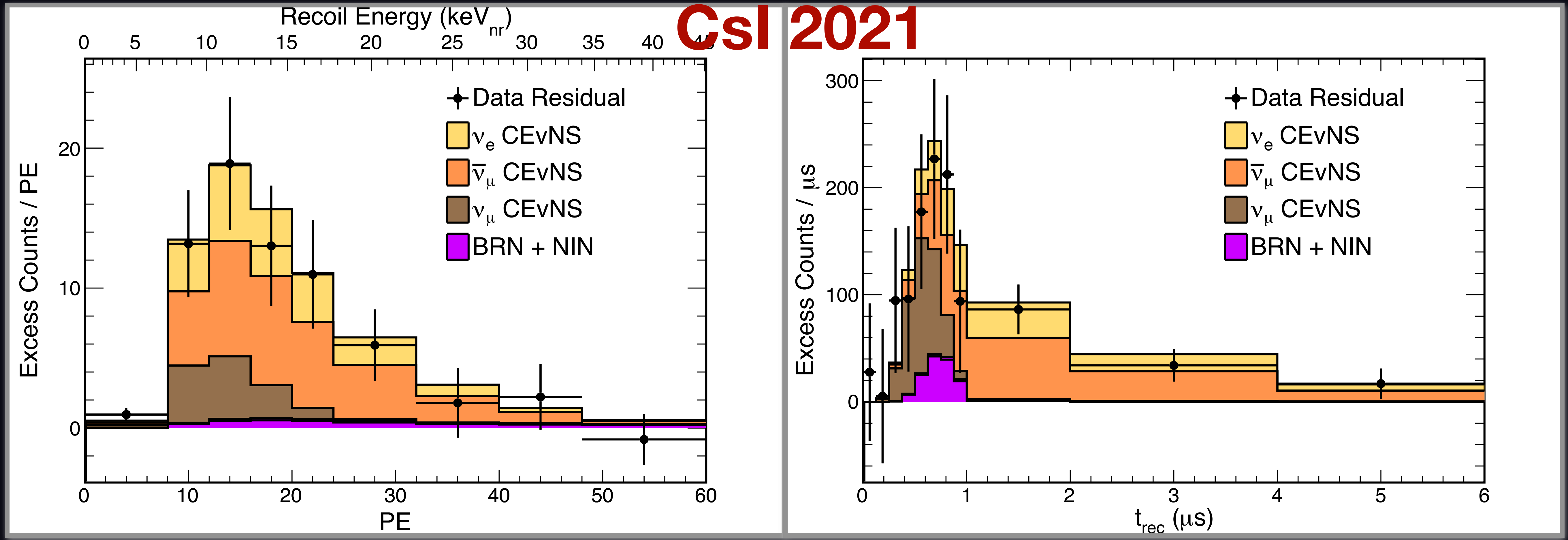


D. Akimov et al. (COHERENT). Phys. Rev. Lett. 126 (2021) 012002

SNS as a neutrino source

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\downarrow$$
$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$





D. Akimov et al. (COHERENT). arXiv:2110.07730 (2021)

CEvNS differential cross section

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

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

Weak charge

$$Q_\mathrm{w} = ZQ_\mathrm{w}^p + NQ_\mathrm{w}^n$$

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

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

Radiative corrections ?

Axial-vector form factor F_A

Negligible ?

Nuclear weak form factor F_W

Phenomenological Helm and Klein-Nystrand

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

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

Chiral EFT: Systematic expansion of nuclear forces and electroweak currents

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

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

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

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

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

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 ???

Workflow of *ab-initio* nuclear calculation

Update

SM/BSM

QCD+ Electroweak

→

Realistic nuclear force

(*NN+NNN*)

- Reproduce the NN scattering data
- Reproduce few-body properties

Chiral EFT, CD-Bonn, Nijmegen, AV18, …

Currents, 0νββ, dark matter, …

→

Renormalization scheme

- Deal with the strong short-range correlations
- Speed up the convergence

SRG, $V_{\mathrm{low}-k}$, OLS, UCOM, G-matrix

→

***Ab-initio* many-body theory**

- From the beginning
- Without any additional parameters or uncontrolled approximations

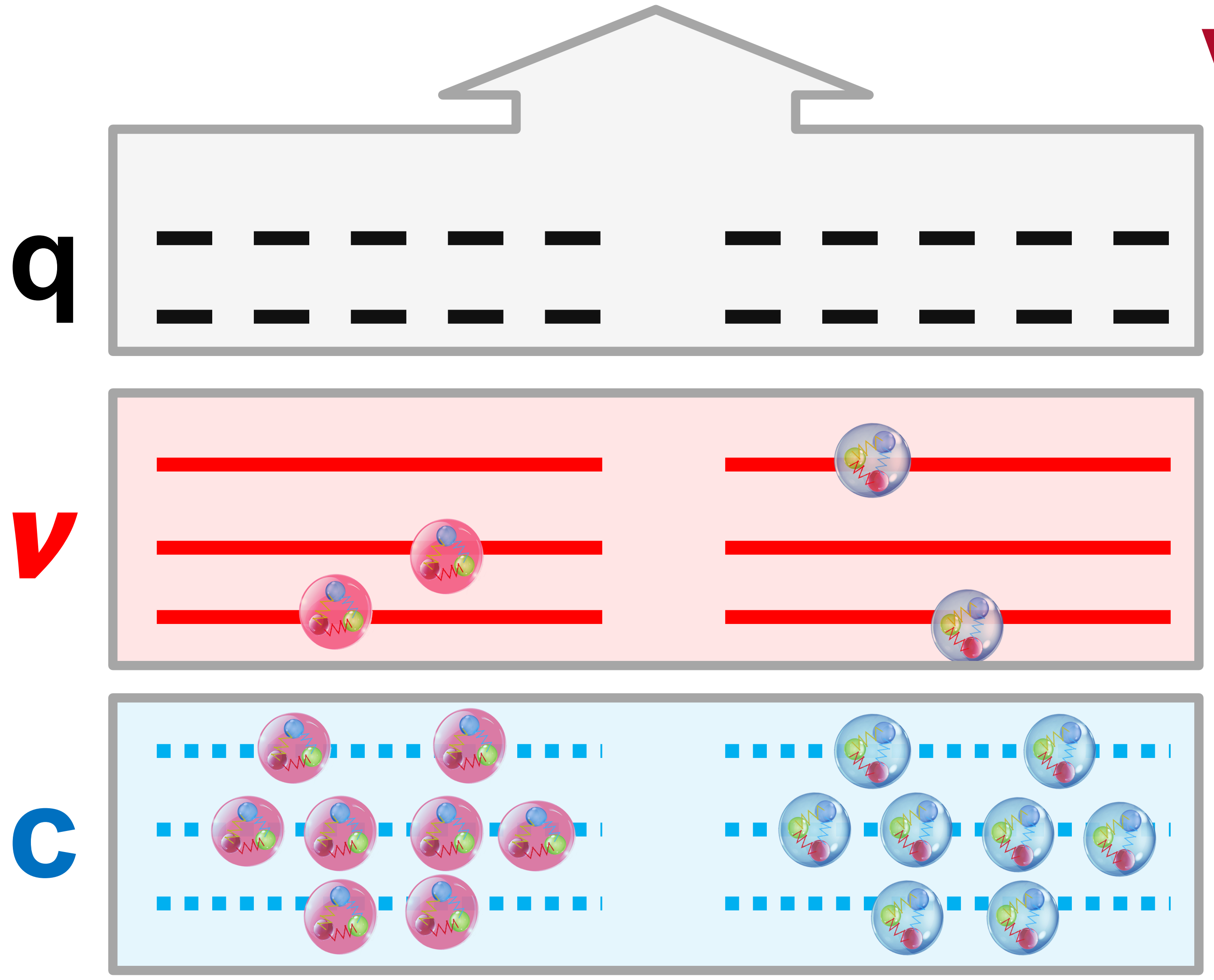
NCSM, GFMC, SCGF, CC, IM-SRG, MBPT, …

→

Describe /predict experimental data

Valence-Space In-Medium Similarity Renormalization Group

drive the Hamiltonian towards a band- or block-diagonal form
via continuous unitary transformation



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

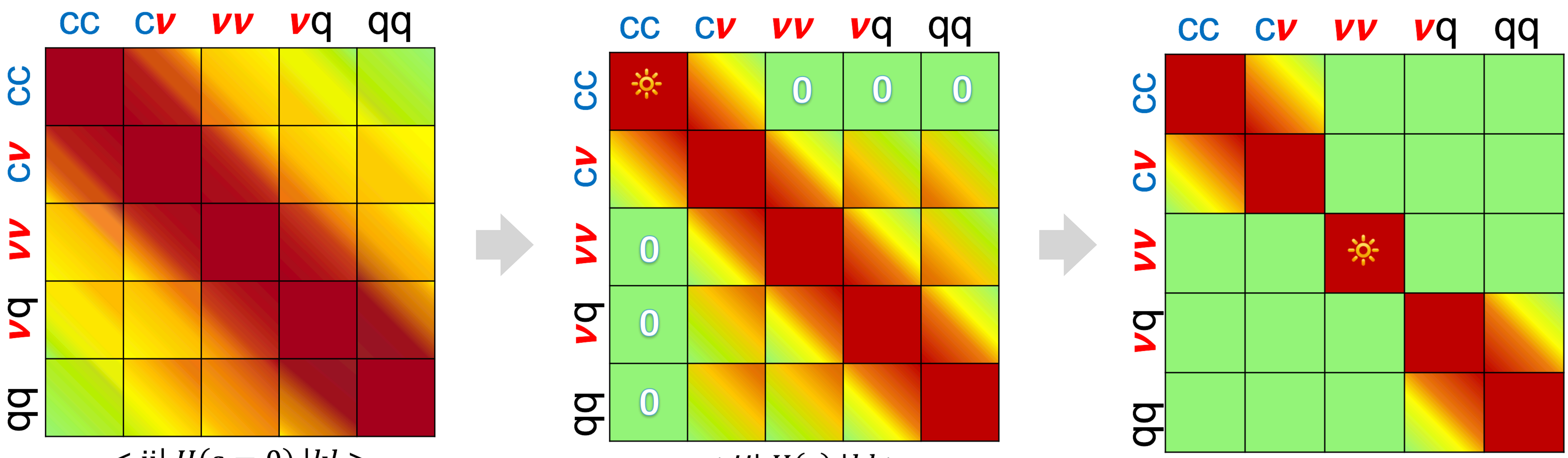
$$H(s) = U(s)HU^{-1}(s) \qquad \mathcal{O}(s) = U(s)\mathcal{O}U^{-1}(s)$$

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

Step1: Decouple core

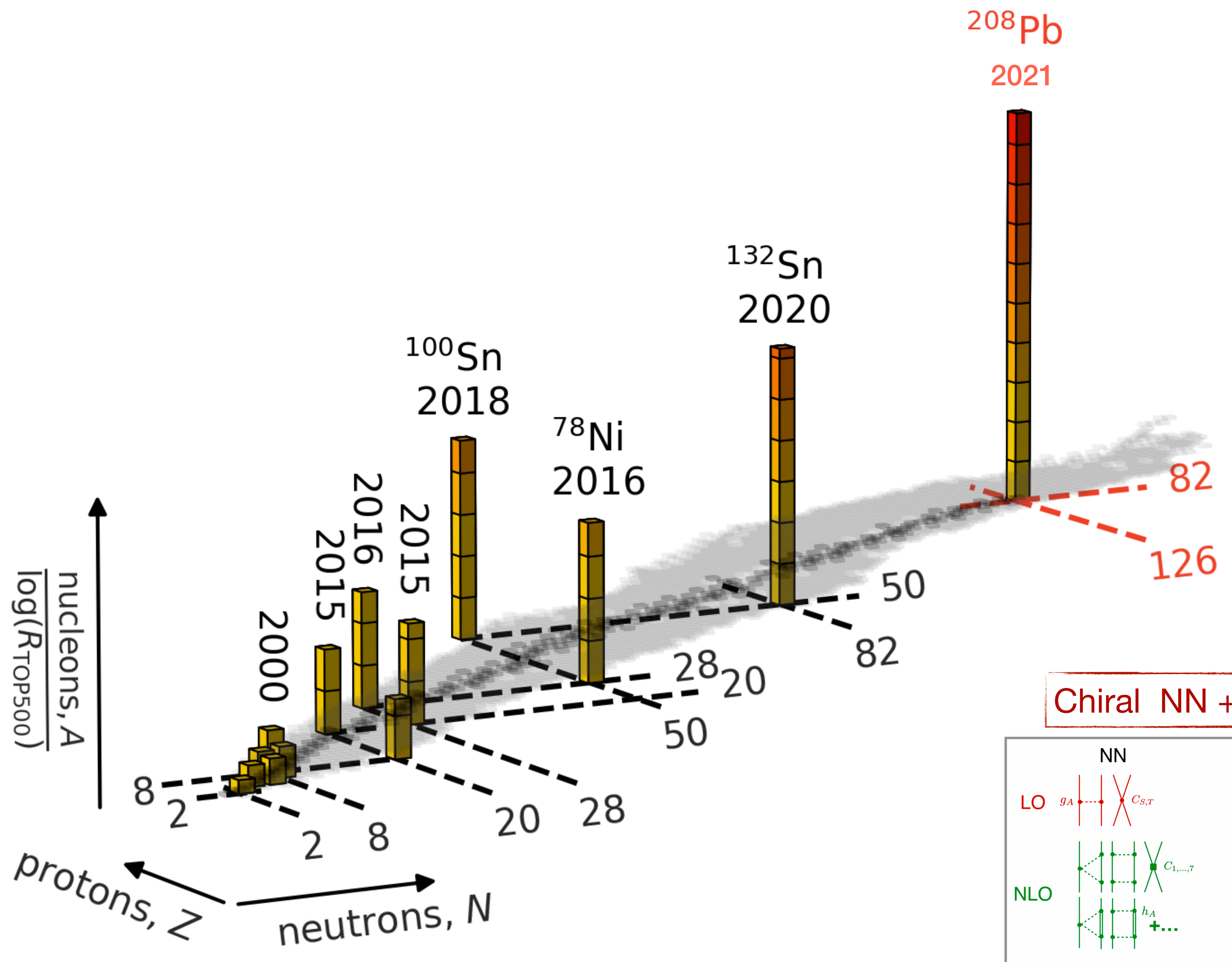
Step2: Decouple valence space

Step3: Decouple additional operators

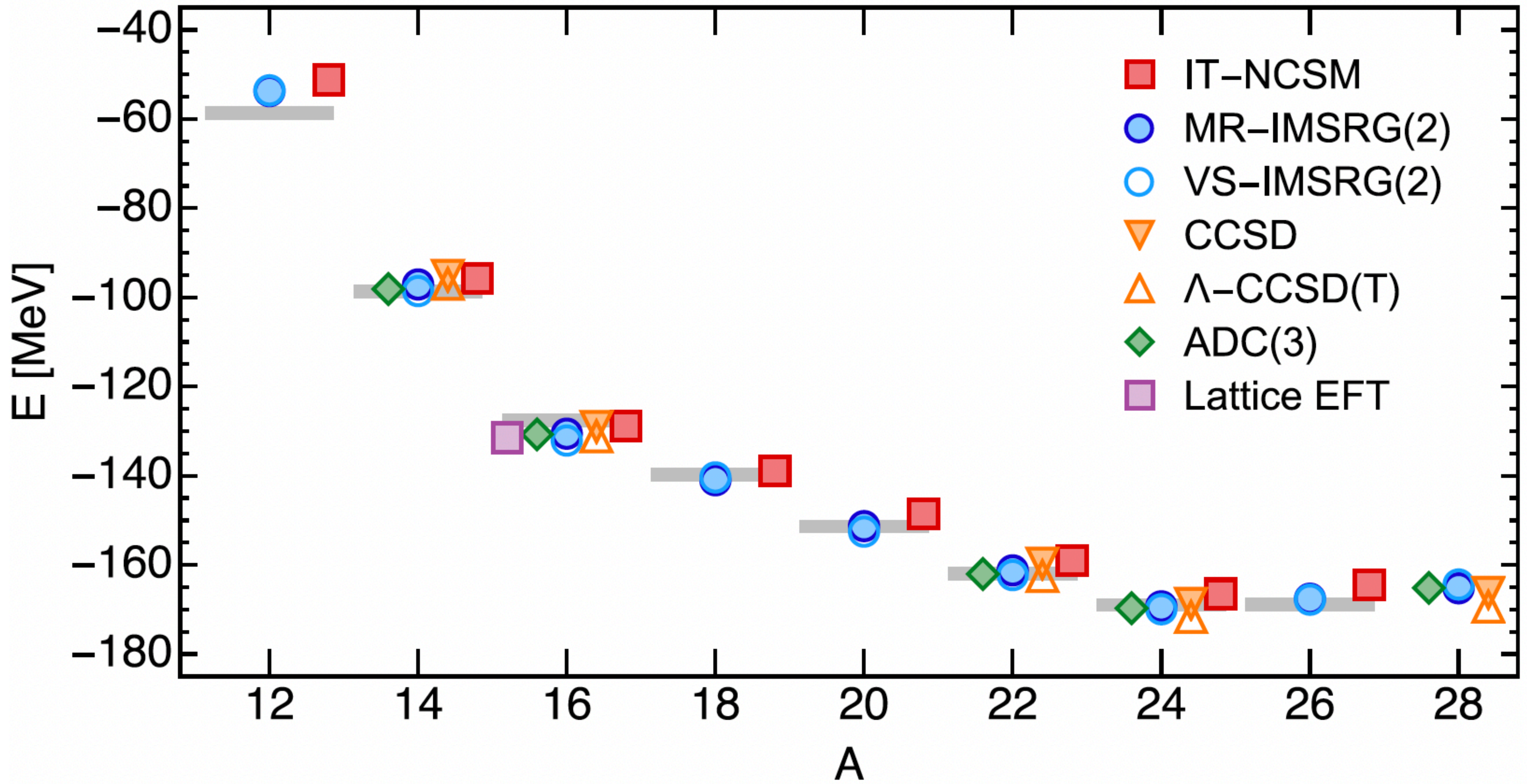


$< ij|\, H(s=0)\, |kl >$ $\qquad$ $< ij|\, H(s)\, |kl >$ $\qquad$ $< ij|\, H(s)\, |kl >$

Ab initio results for ^{208}Pb region

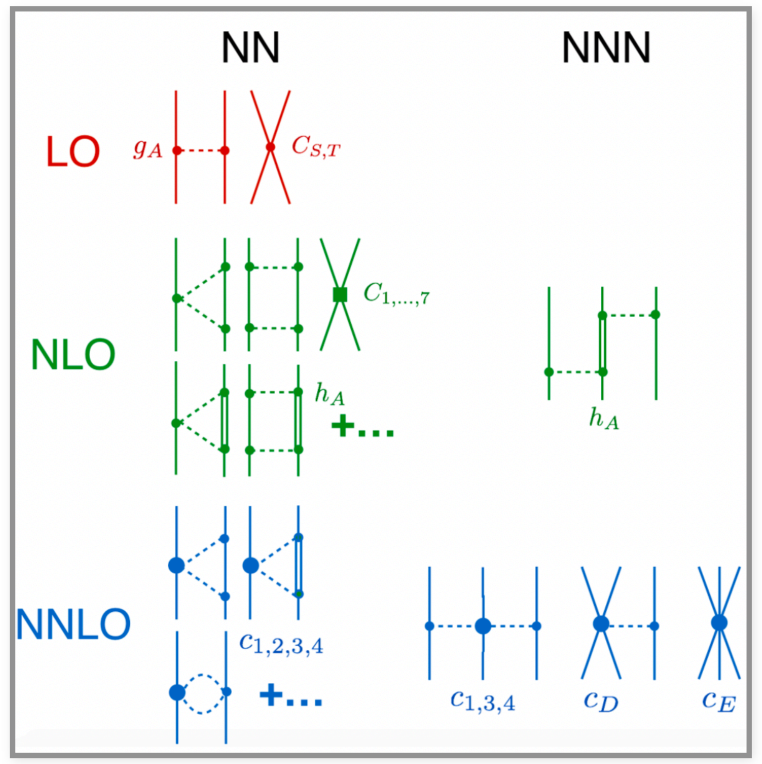


Precision of different methods: 1~2%



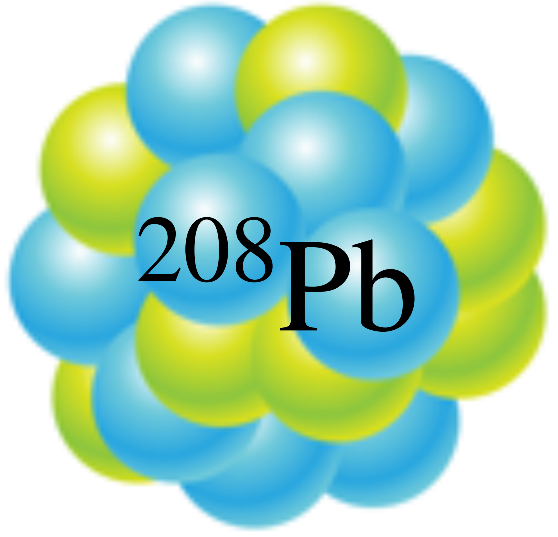
H. Hergert, Front. Phys. 8 (2020) 379

Chiral NN + 3N

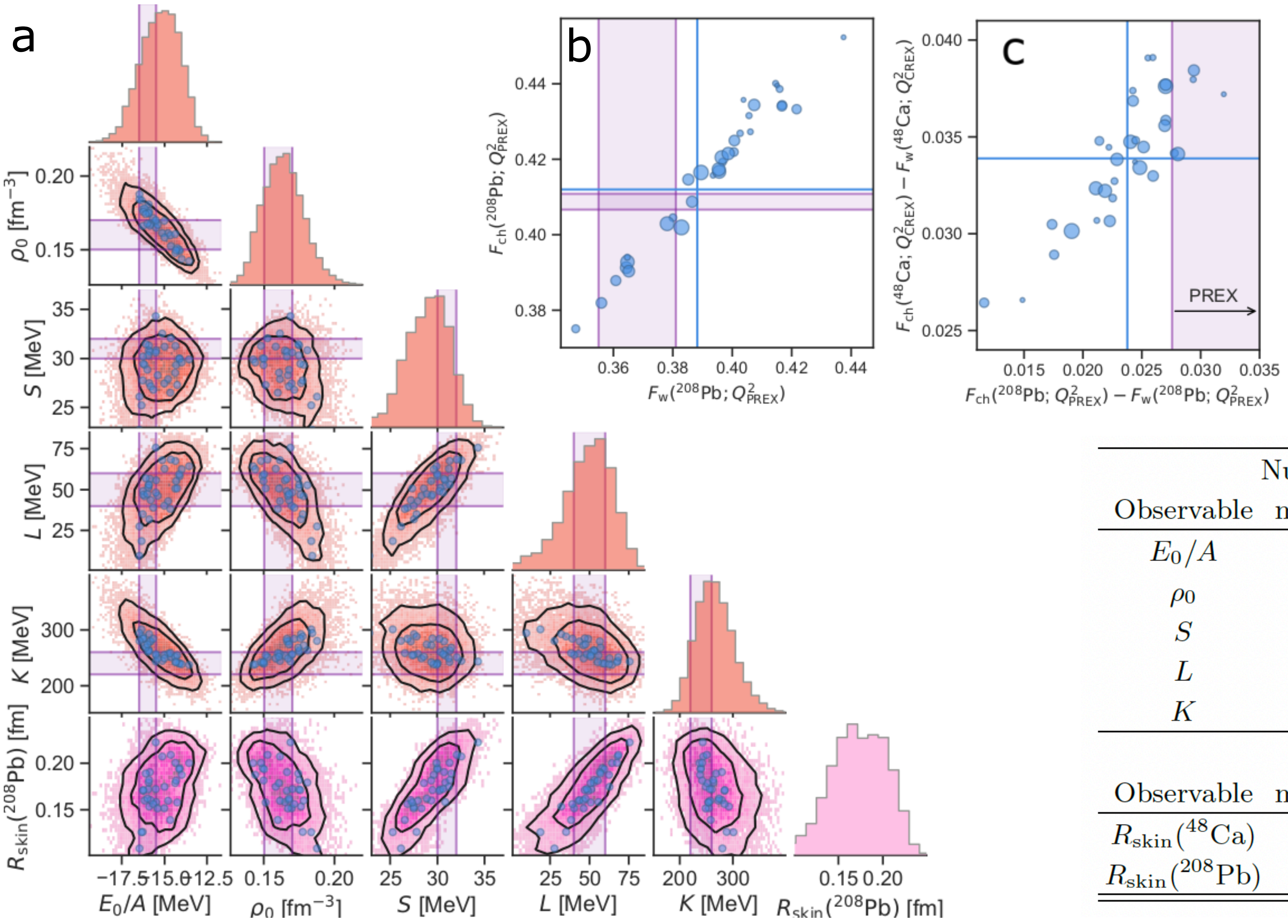


History matching
Emulator technology
Statistical tools

New 3N storage scheme
IMSRG, CC



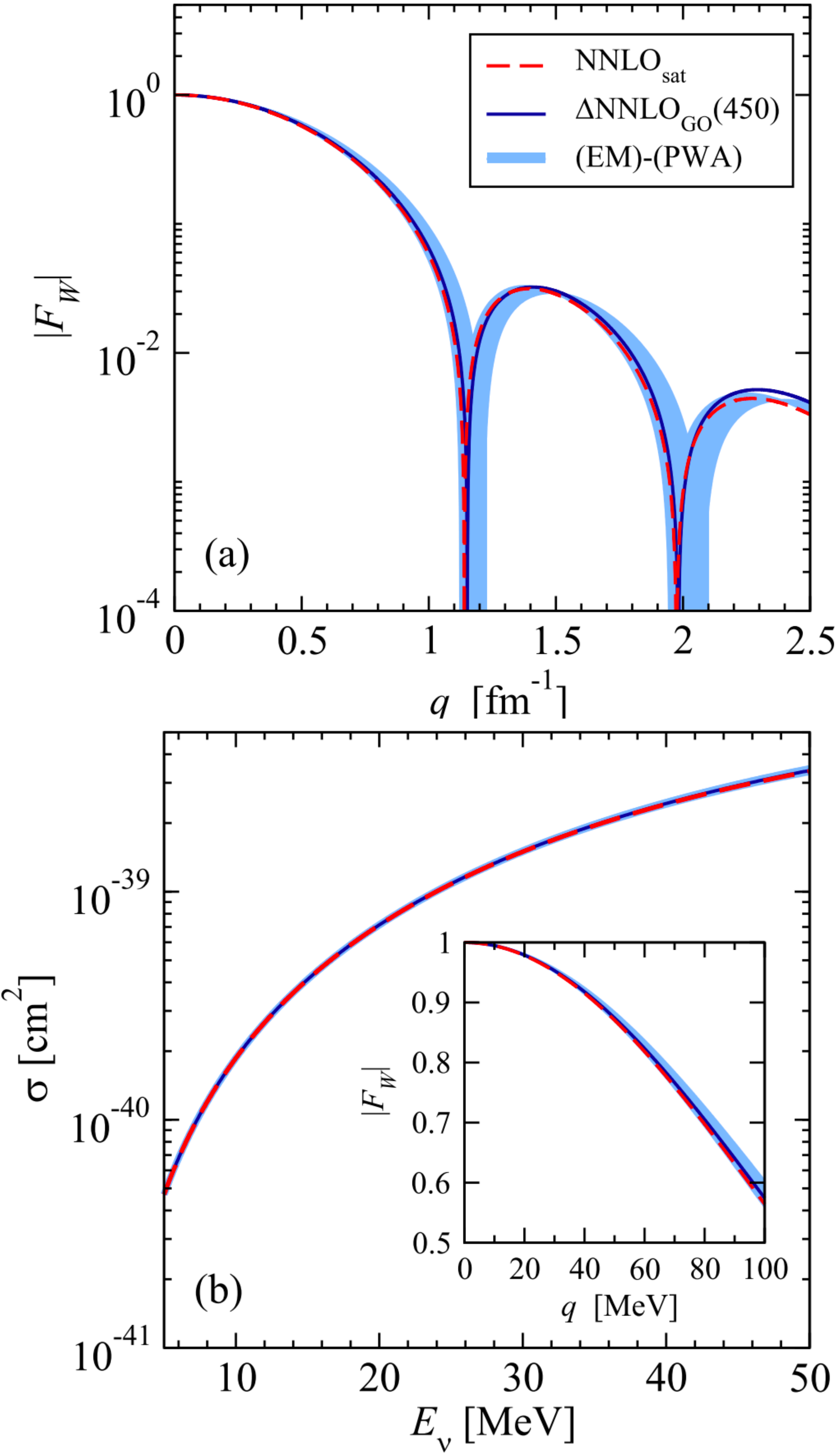
Ab initio predictions for ^{48}Ca, ^{208}Pb and nuclear matter

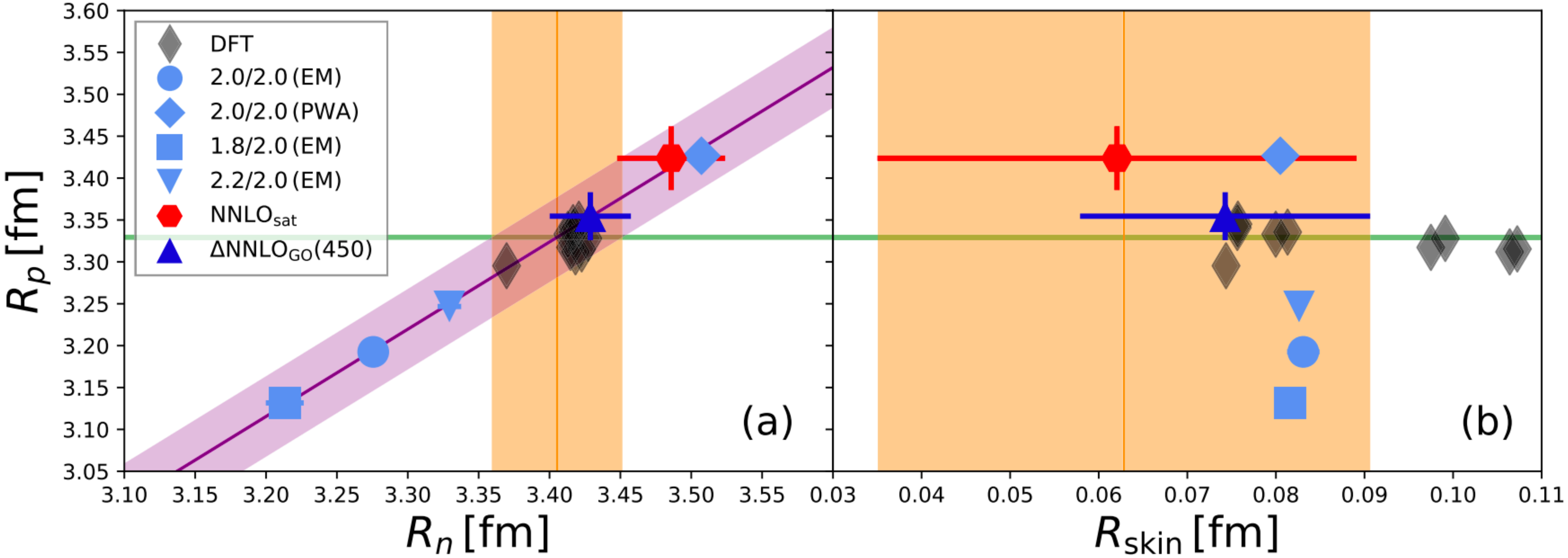


Nuclear matter properties			
Observable	median	68% CR	90% CR
E_0/A	-15.2	$[-16.3, -14.0]$	$[-17.2, -13.5]$
ρ_0	0.163	[0.147, 0.175]	[0.140, 0.186]
S	29.1	[26.6, 31.3]	[25.132.8]
L	50.3	[37.2, 68.1]	[22.6, 75.8]
K	264	[227, 297]	[210, 328]
Neutron skins			
Observable	median	68% CR	90% CR
$R_{\rm skin}(^{48}{\rm Ca})$	0.164	[0.141, 0.187]	[0.123, 0.199]
$R_{\rm skin}(^{208}{\rm Pb})$	0.171	[0.139, 0.200]	[0.120, 0.221]

BS Hu, WG Jiang, T Miyagi, ZH Sun, *et al.*, arXiv:2112.01125v1 (2021)

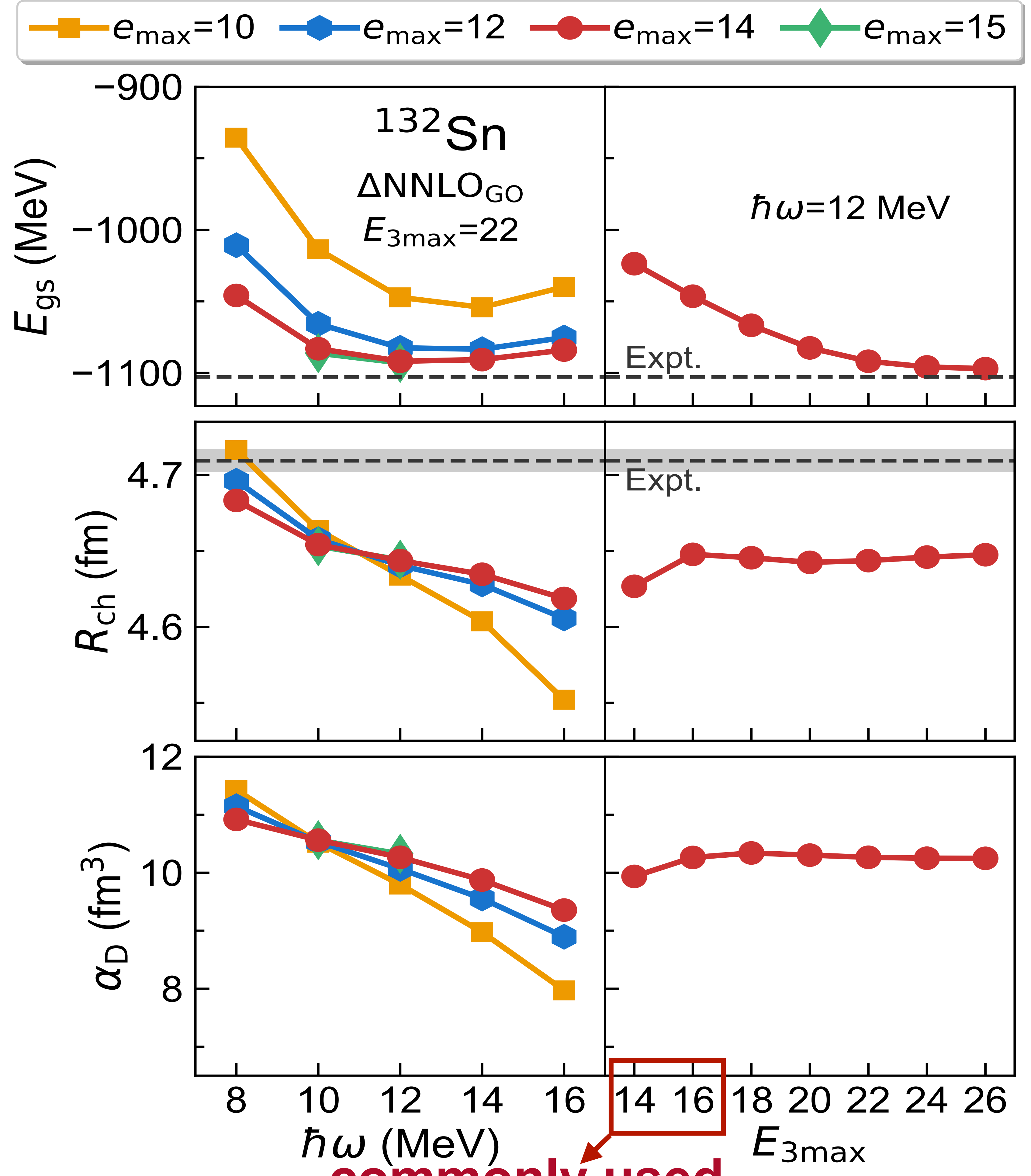
Ab initio coupled-cluster calculations of CEvNS in ^{40}Ar





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

Heavy nuclei is challenging current *ab-initio* approaches



commonly used

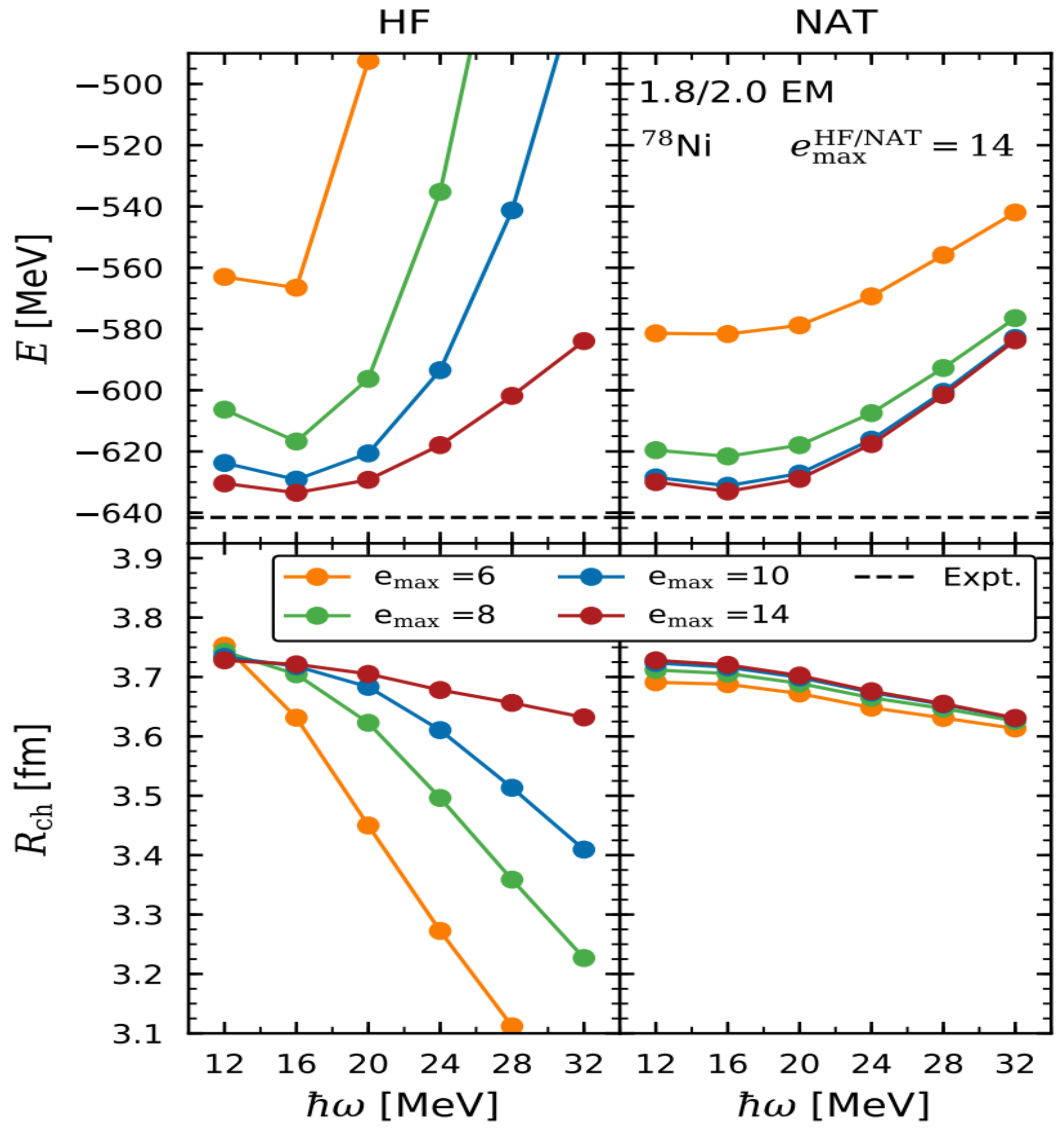
BS Hu, et al., in prep (2022)

New 3N storage scheme developed by T. Miyagi et al.

Natural orbitals (NAT)

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

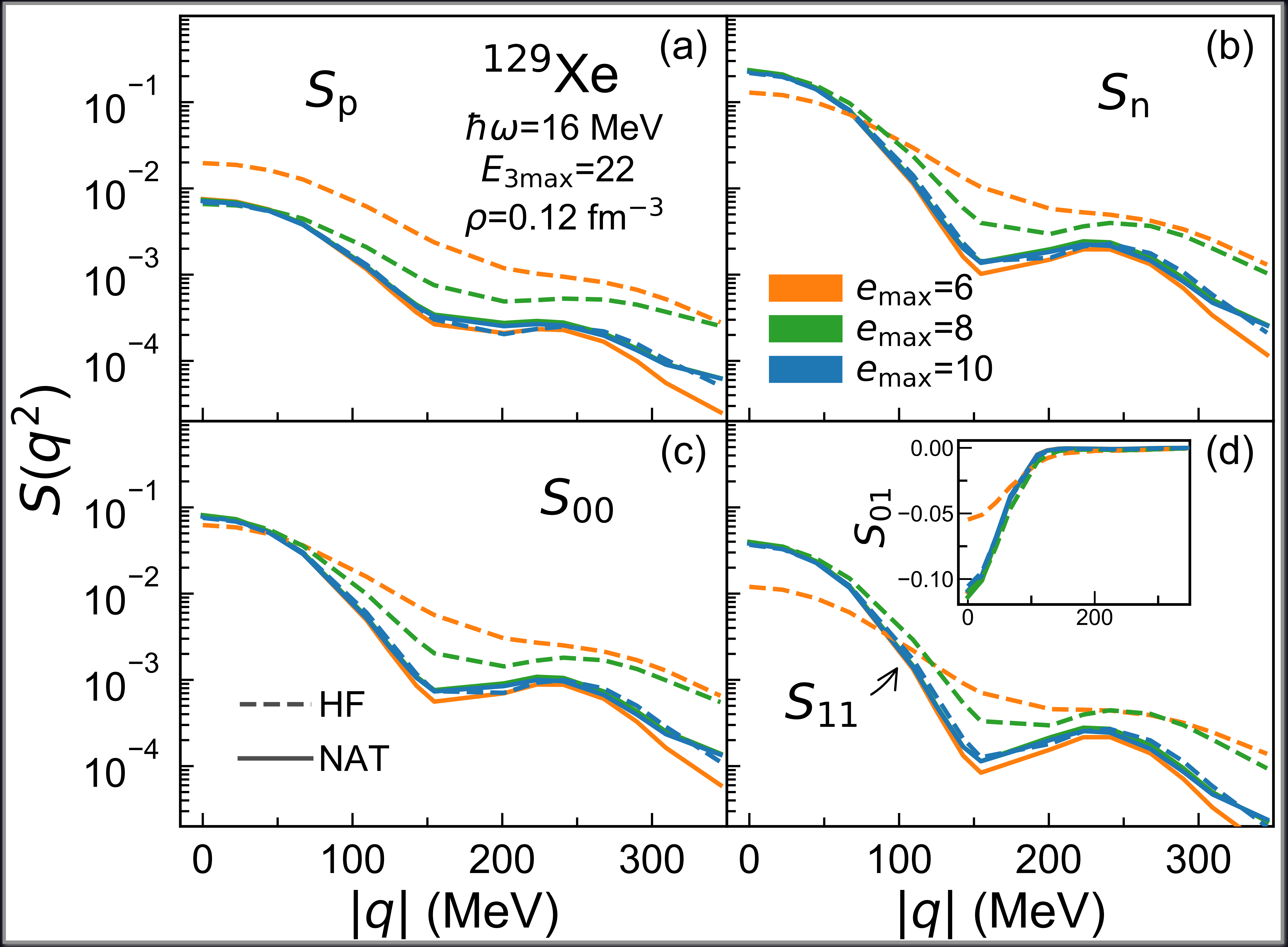
$$|\Psi\rangle \approx \left|\Psi^{(0)}\right\rangle + \left|\Psi^{(1)}\right\rangle + \left|\Psi^{(2)}\right\rangle$$



J. Hoppe, et al., PRC 103 (2021) 014321

Need larger E_{3max} for heavy nuclei! E_{3max}=14 in most *ab-initio* calculations!
Natural orbital offers significant computational savings, and opens *ab-initio* calculations for heavy nuclei!

VS-IMSRG convergence for elastic spin-dependent WIMP scattering off heavy nuclei

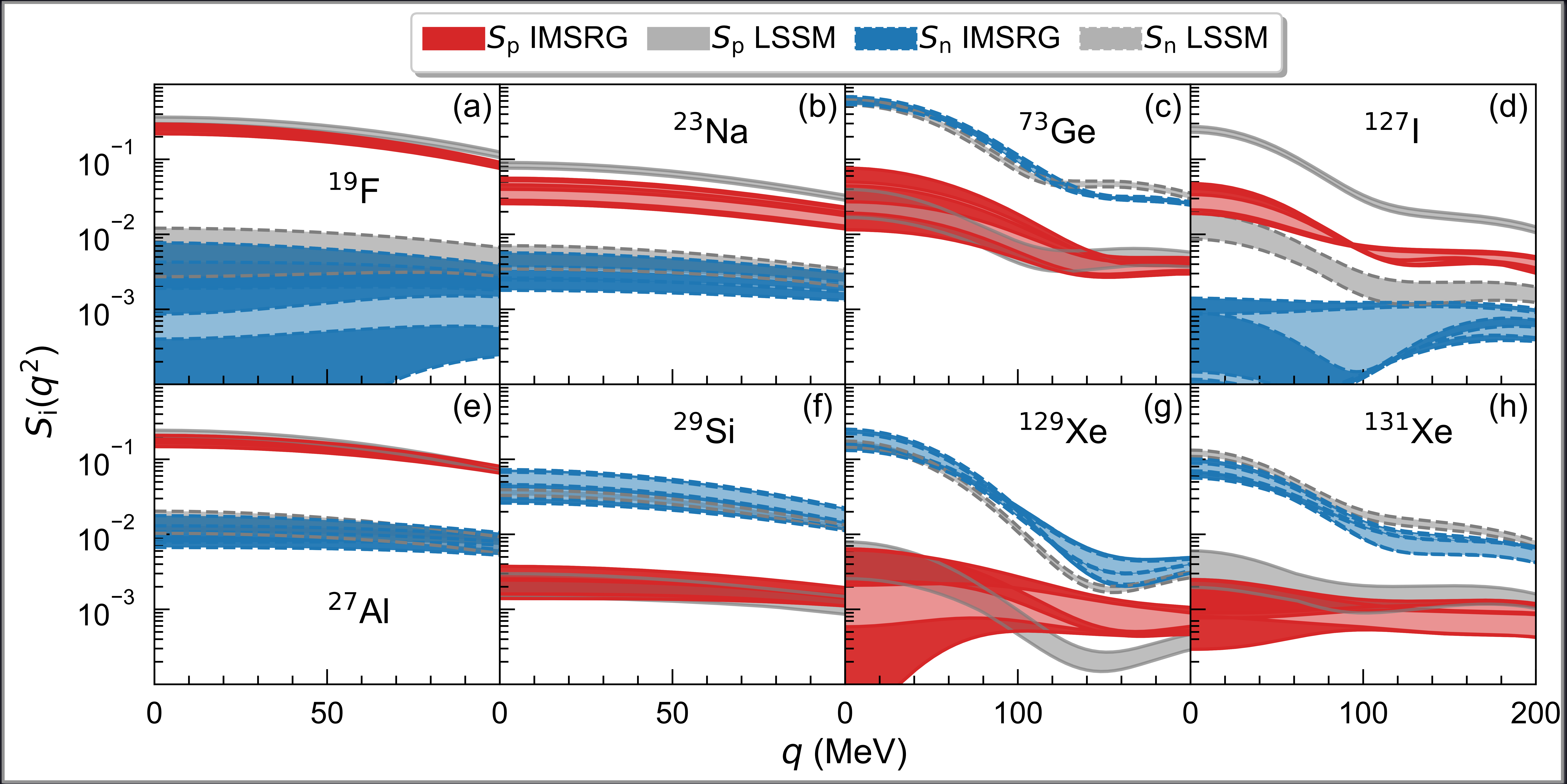


- Tensor operators are heavy tasks for IMSRG transformation
- Many q points need to calculate many operators

Large E_{3max} and natural orbital allow VS-IMSRG possible for heavy nuclei!

B.S. Hu, et al, Phys. Rev. Lett 128 (2022) 072502

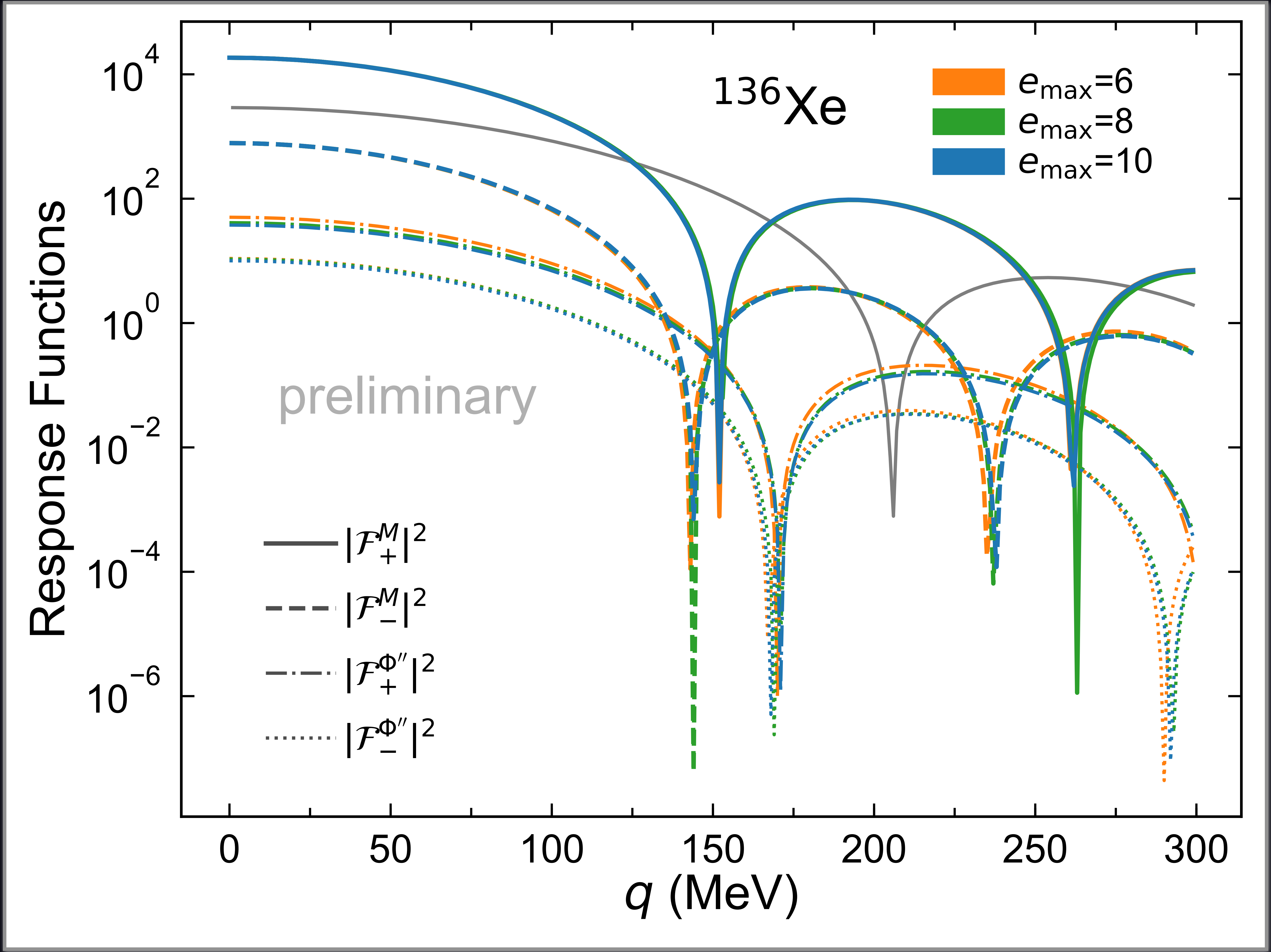
VS-IMSRG structure factors for spin-dependent dark matter direct detection



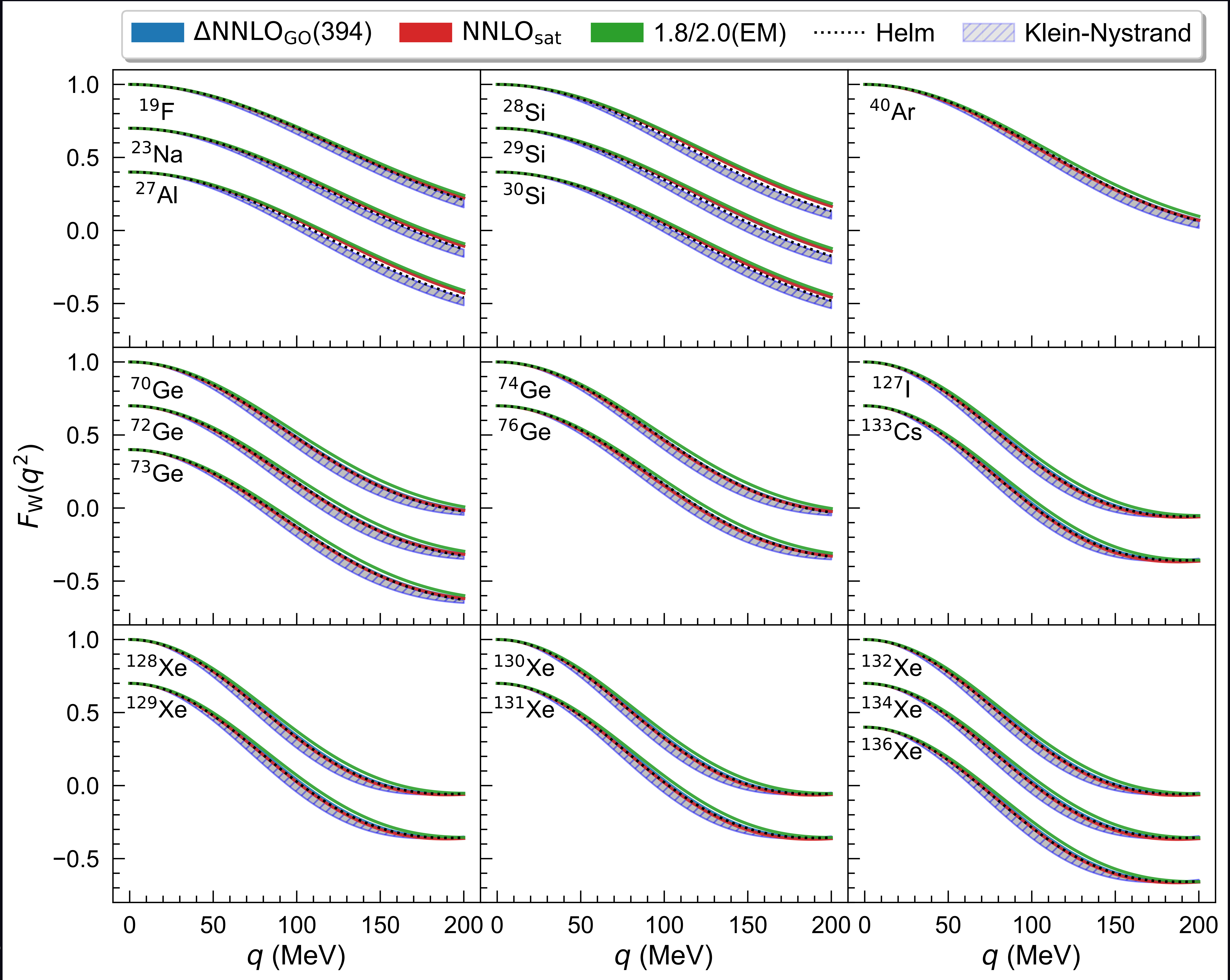
B.S. Hu, et al, Phys. Rev. Lett 128 (2022) 072502

Convergence of nuclear response functions within NAT basis

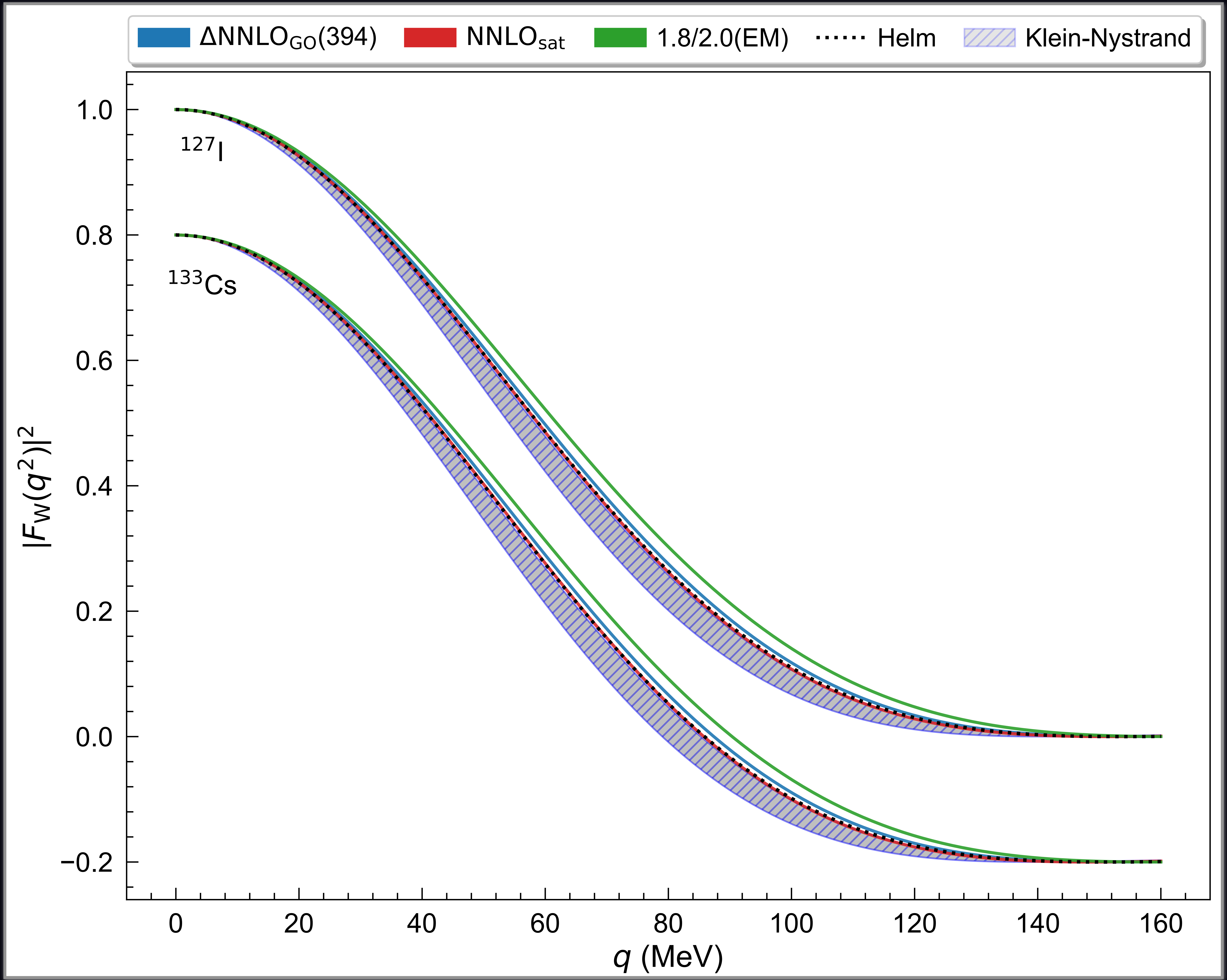
$\mathscr{F}_\tau^M, \mathscr{F}_\tau^{\Phi''}, \mathscr{F}_\tau^{\Sigma'}$

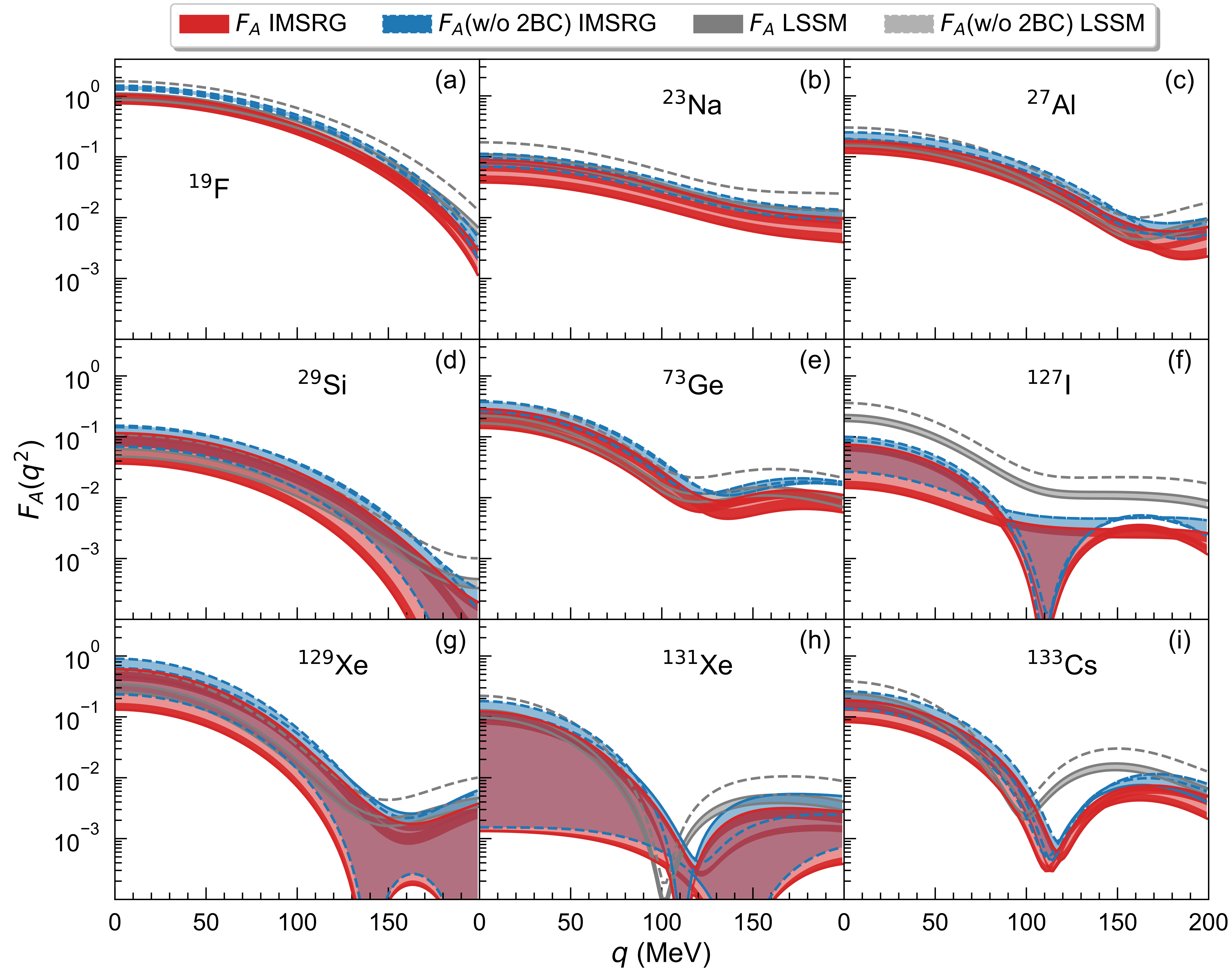


BS Hu, et al., In preparation (2022)



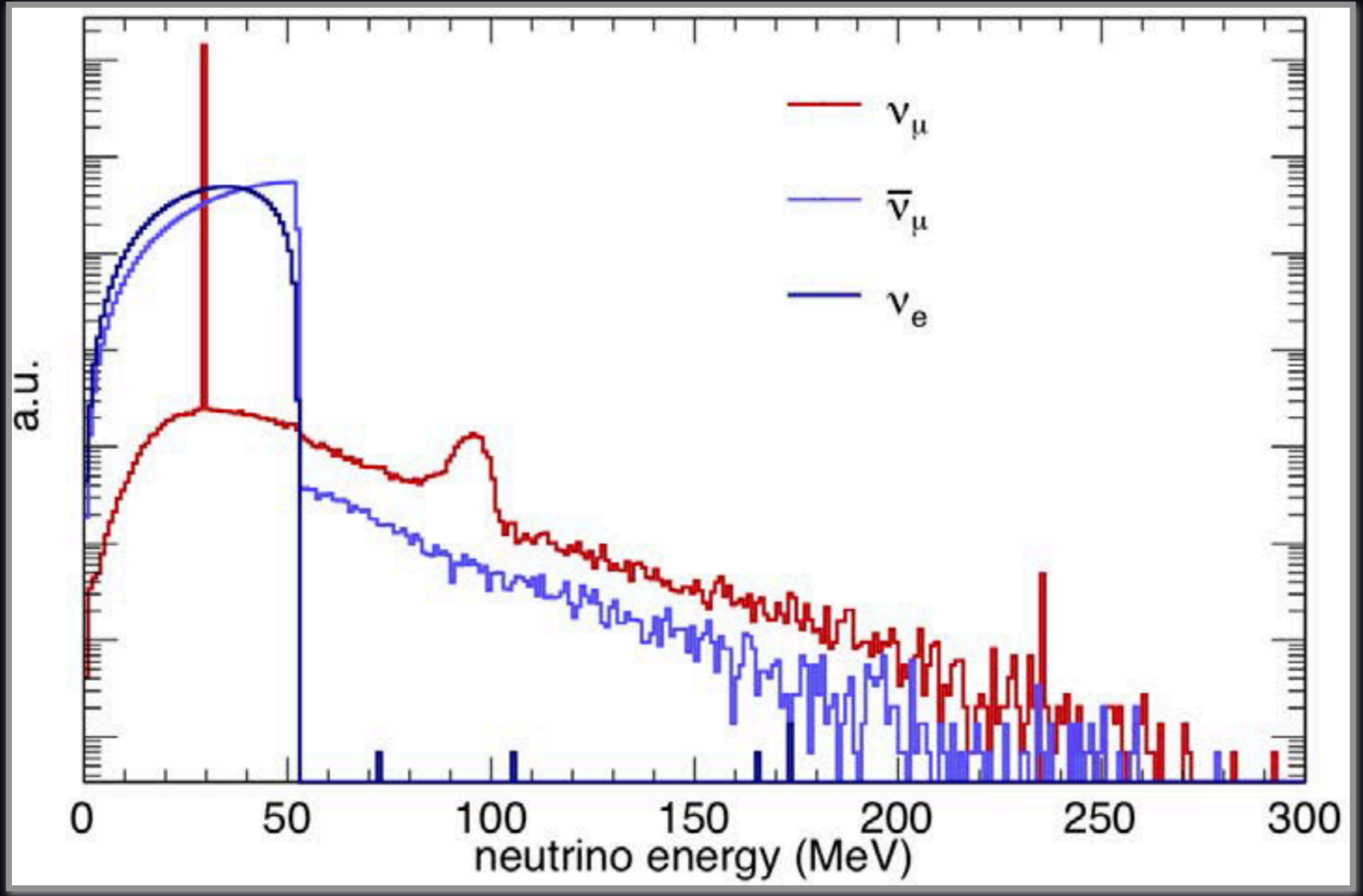
BS Hu, et al.,
In preparation (2022)


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)

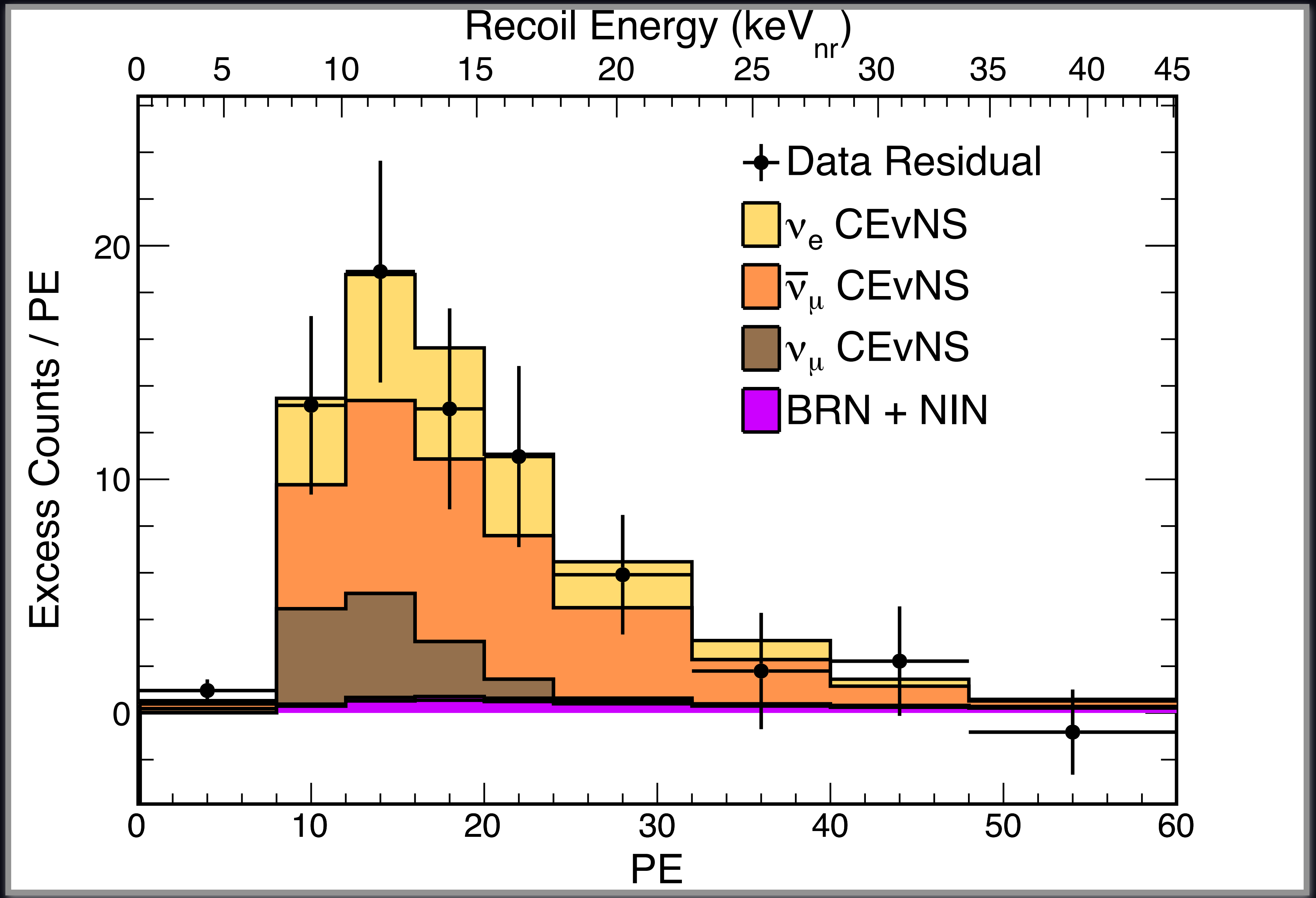


F_A IMSRG
F_A(w/o 2BC) IMSRG
F_A LSSM
F_A(w/o 2BC) LSSM
(a) ^{19}F
(b) ^{23}Na
(c) ^{27}Al
(d) ^{29}Si
(e) ^{73}Ge
(f) ^{127}I
(g) ^{129}Xe
(h) ^{131}Xe
(i) ^{133}Cs
$F_A(q^2)$
q (MeV)

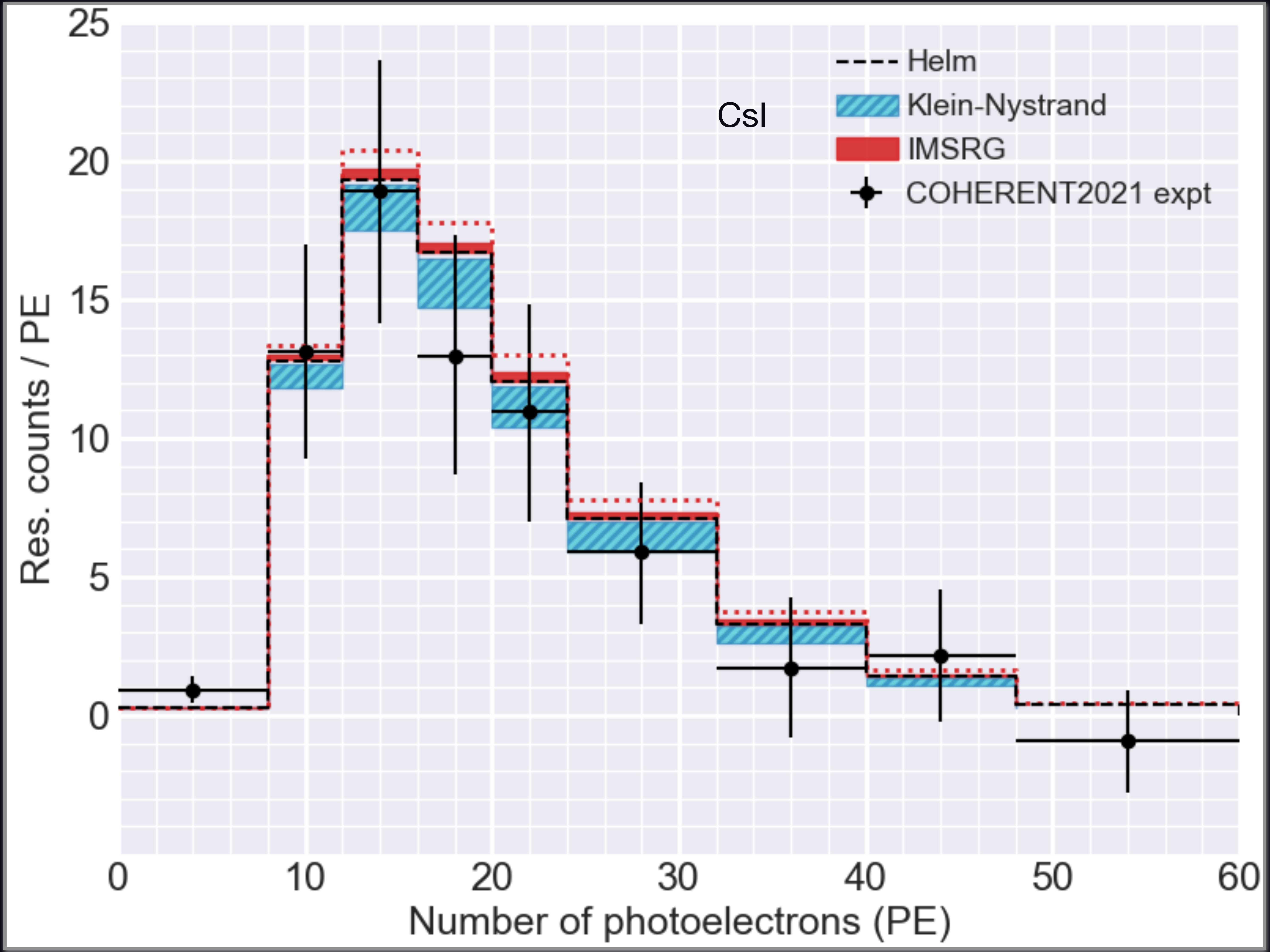
$$\frac{dR}{dT} = \sum_i \left[N_{\text{target}} X_i \mathcal{N}_\nu \int_{E_\nu^{\min}}^{E_\nu^{\max}} \phi(E_\nu) \frac{d\sigma_i}{dT} dE_\nu \right]$$



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

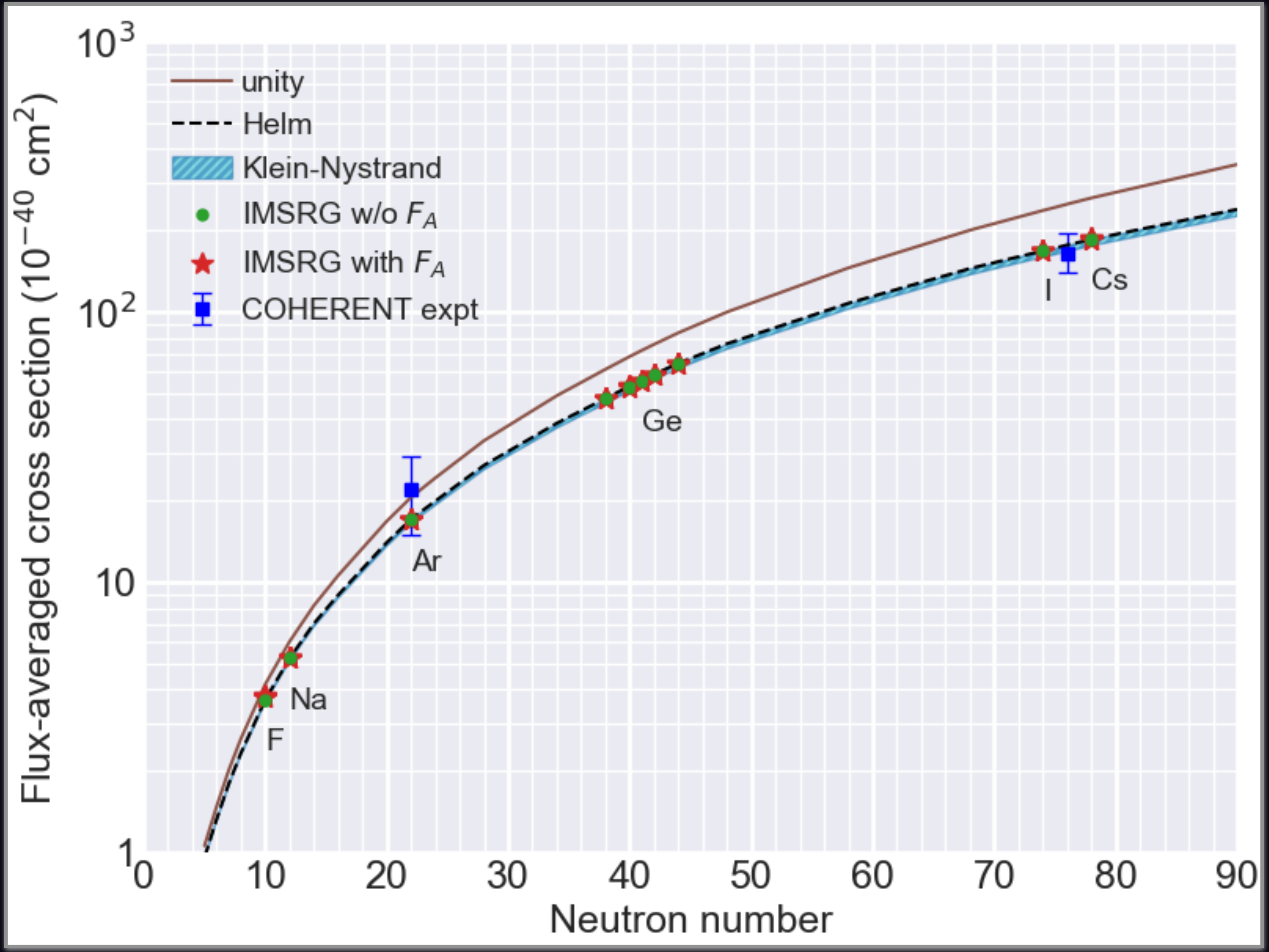


D. Akimov et al. (COHERENT). arXiv:2110.07730 (2021)



BS Hu, et al., In preparation (2022)

Cross-section averaged over the SNS spectrum



BS Hu, et al., In preparation (2022)

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

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

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

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

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

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

- **Weak charges:** 1.5% level

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

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

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

  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 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

Inelastic scattering
BSM constrains

IMSRG gives converged calculation in heavy nuclei;
Large E_{3max}
VS-IMSRG within natural orbital

TRIUMF

Collaborators:

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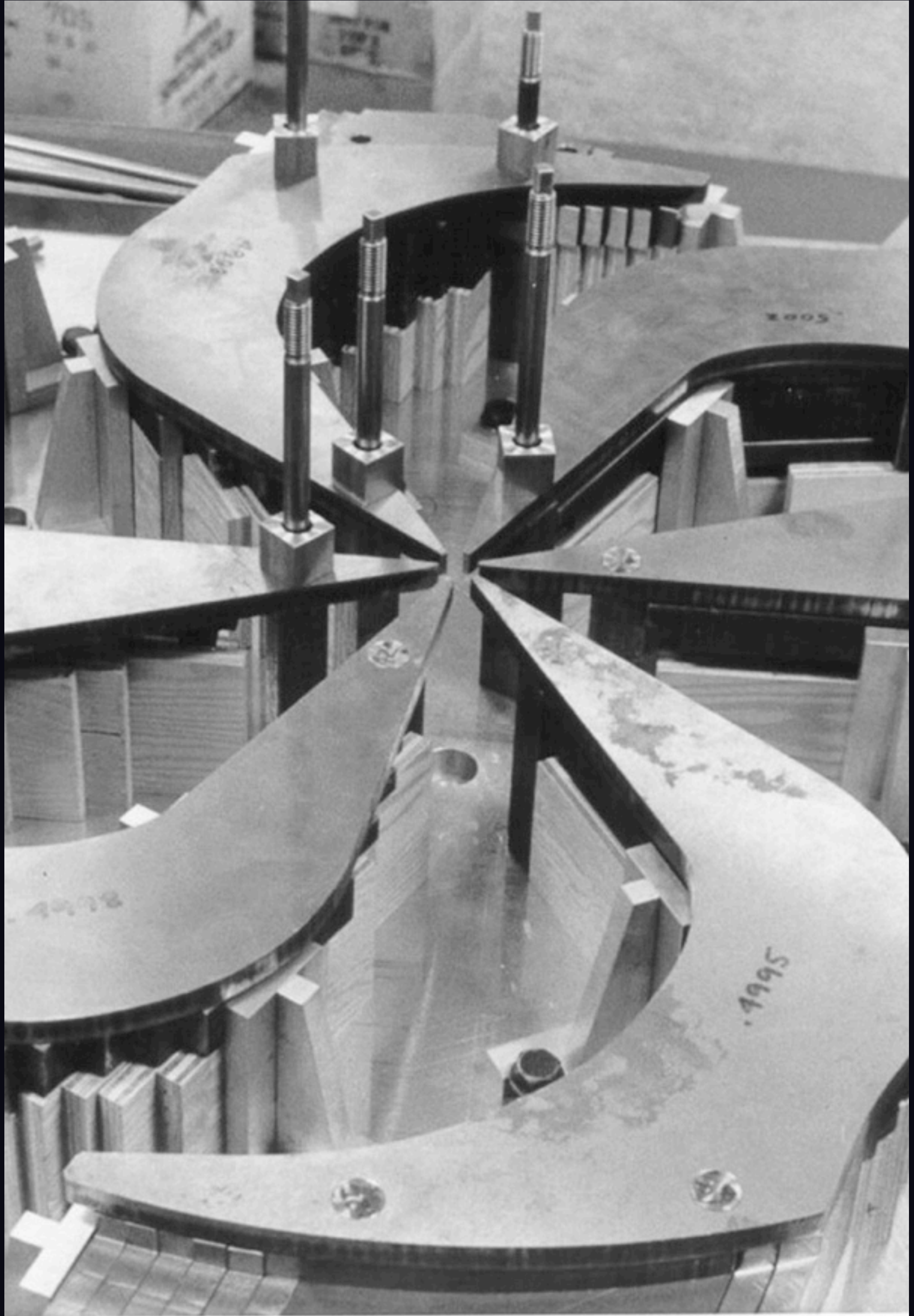
Thomas Papenbrock (U Tennessee)
Mathieu Bruneault (UBC)
José Padua (Perimeter Inst.)
Samuel Leutheusser (MIT)

Chalmers UT:
Weiguang Jiang
Andreas Ekström
Christian Forssén

U Durham:
Ian Vernon

Thank you
Merci



Discovery, accelerated