Electroweak Processes on light nuclei

Lepton interactions with Nucleons and Nuclei

Marciana (Isola d'Elba), Italy, September 6, 2023

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Motivations and outline

The predictive power of EFTs electroweak currents

- We need nuclear currents reliable in a region of momentum transfer of few GeVs (DUNE, HyperKamiokande,…)
- Obtain predictions in an overlap region with higher energy theories

Test of the EM Currents on electrons elastic scattering Magnetic form factors (MFF) using χEFT

Phys. Rev. C 106, 044001 (2022)

- What are the minimal ingredients that bind nuclei?
- Can we predict also electromagnetic observables with these minimal ingredients?

Light nuclei magnetic moments in pionless EFT using the neural-network quantum states

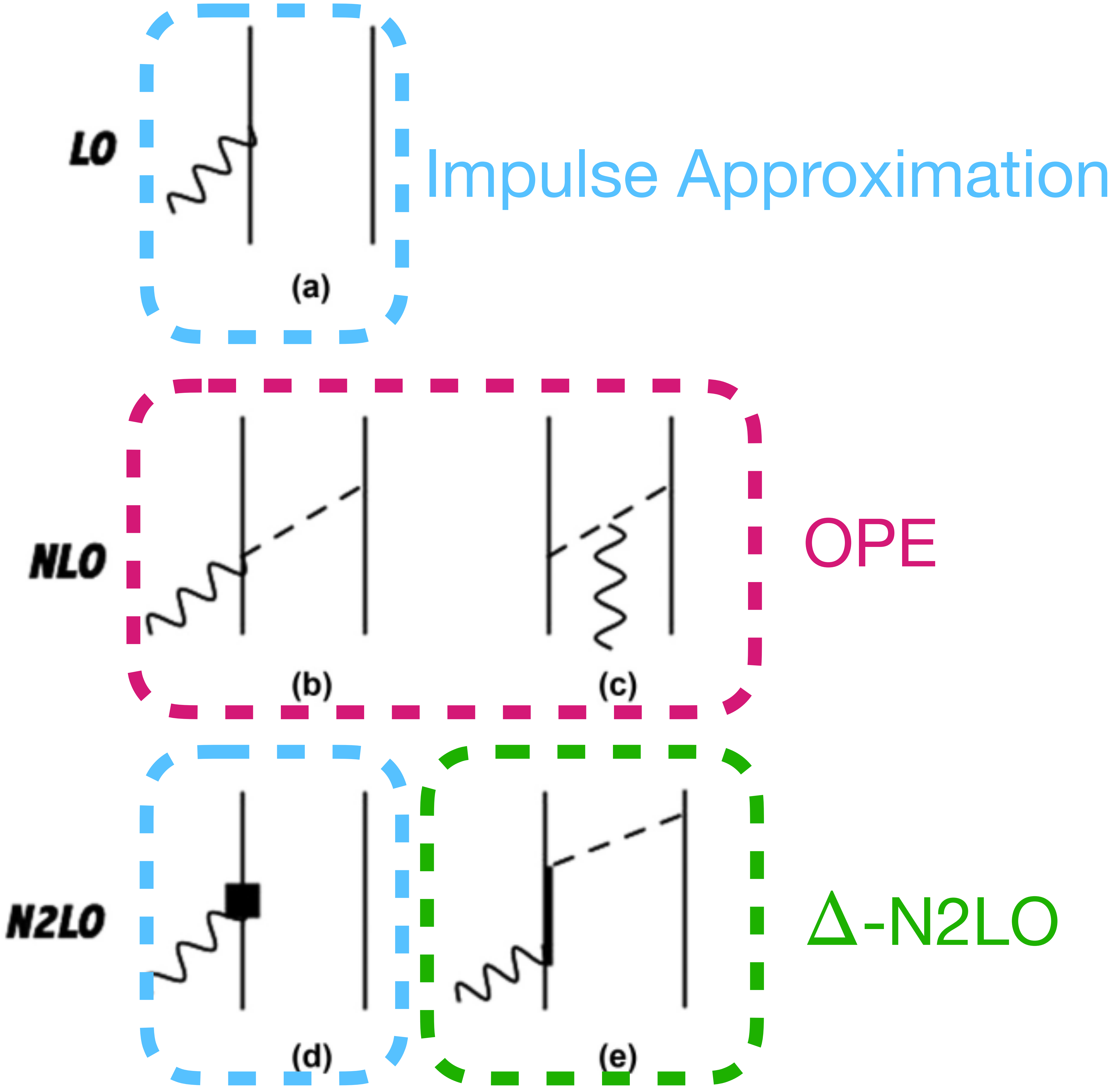
arXiv:2308.16266 (2023)

Part I

with R. Schiavilla

The theory (up to N2LO)

- Chiral expansion of the EM currents
- Two nuclear interactions: Norfolk [1] and EMN [2]
- Currents from [PRC 80, 034004 (2009) and PRC 99, 034005 (2019)]
- Up to N2LO consistent with [H. Krebs, EPJA 56, 234 (2020)]



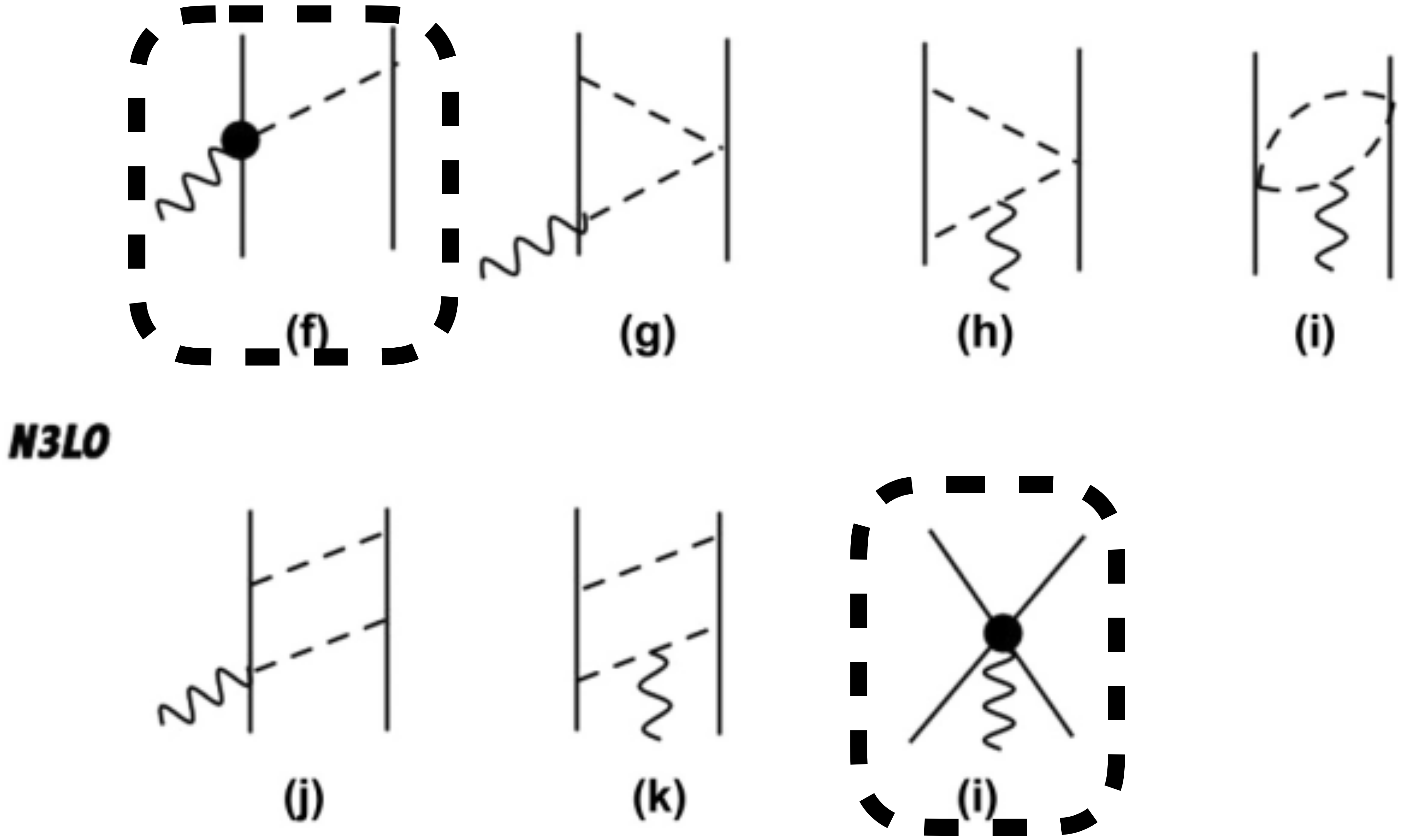
[1-M. Piarulli, et al., PRC 94, 054007 (2016)]
[2-D.R. Entem, et al. PRC 96, 024004 (2017)]

The theory (N3LO)

d_2^V d_3^V d_2^S N3LO-OPE

Some notes on N3LO:

- Unconsistency with Bochum group currents
- Is chiral symmetry violated?
- Current is not fully conserved



d_1^V d_1^S contact terms

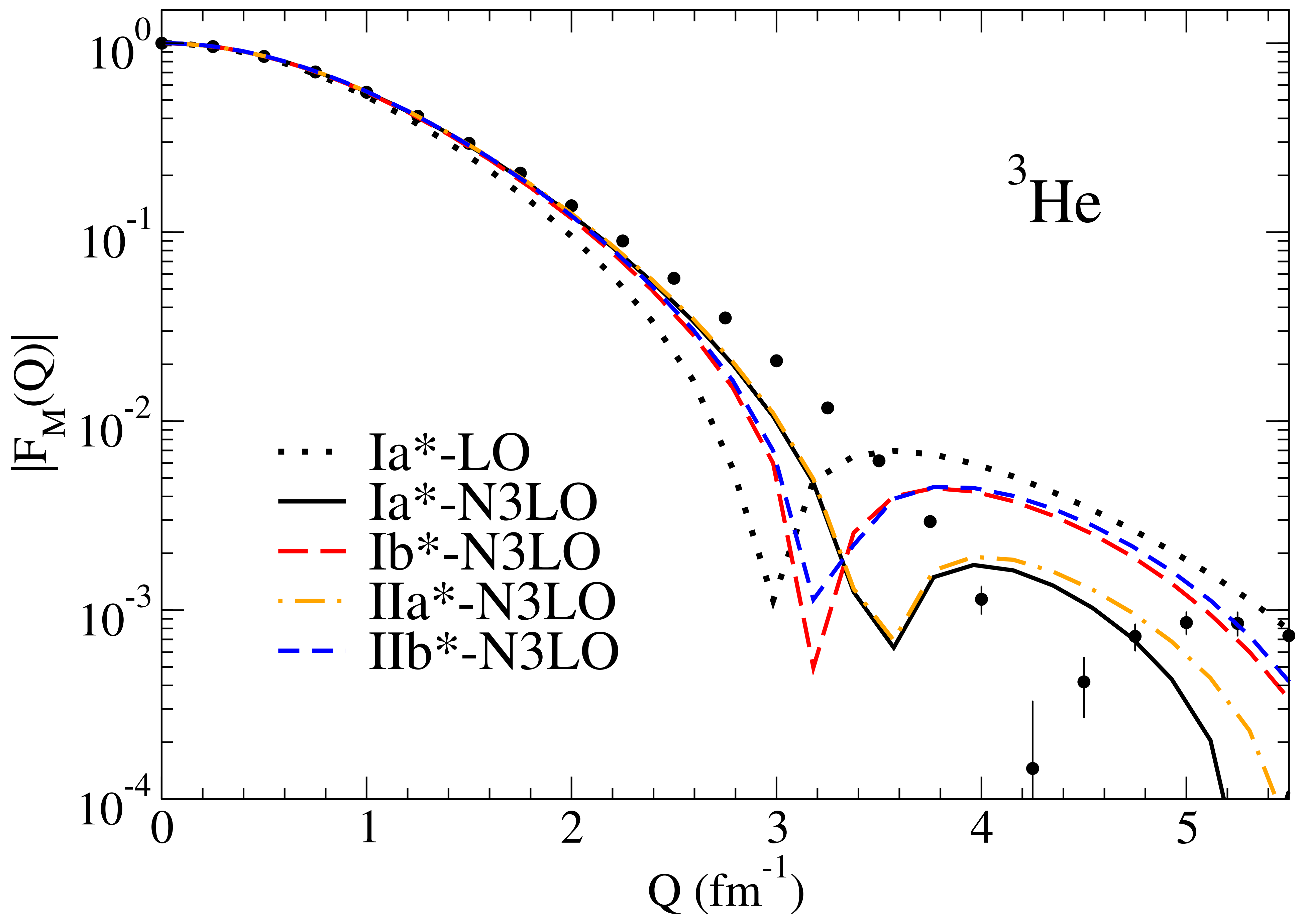
"Semi-phenomenological" χEFT currents

Red: isoscalar Blue: isovector

How to fix the LECs I

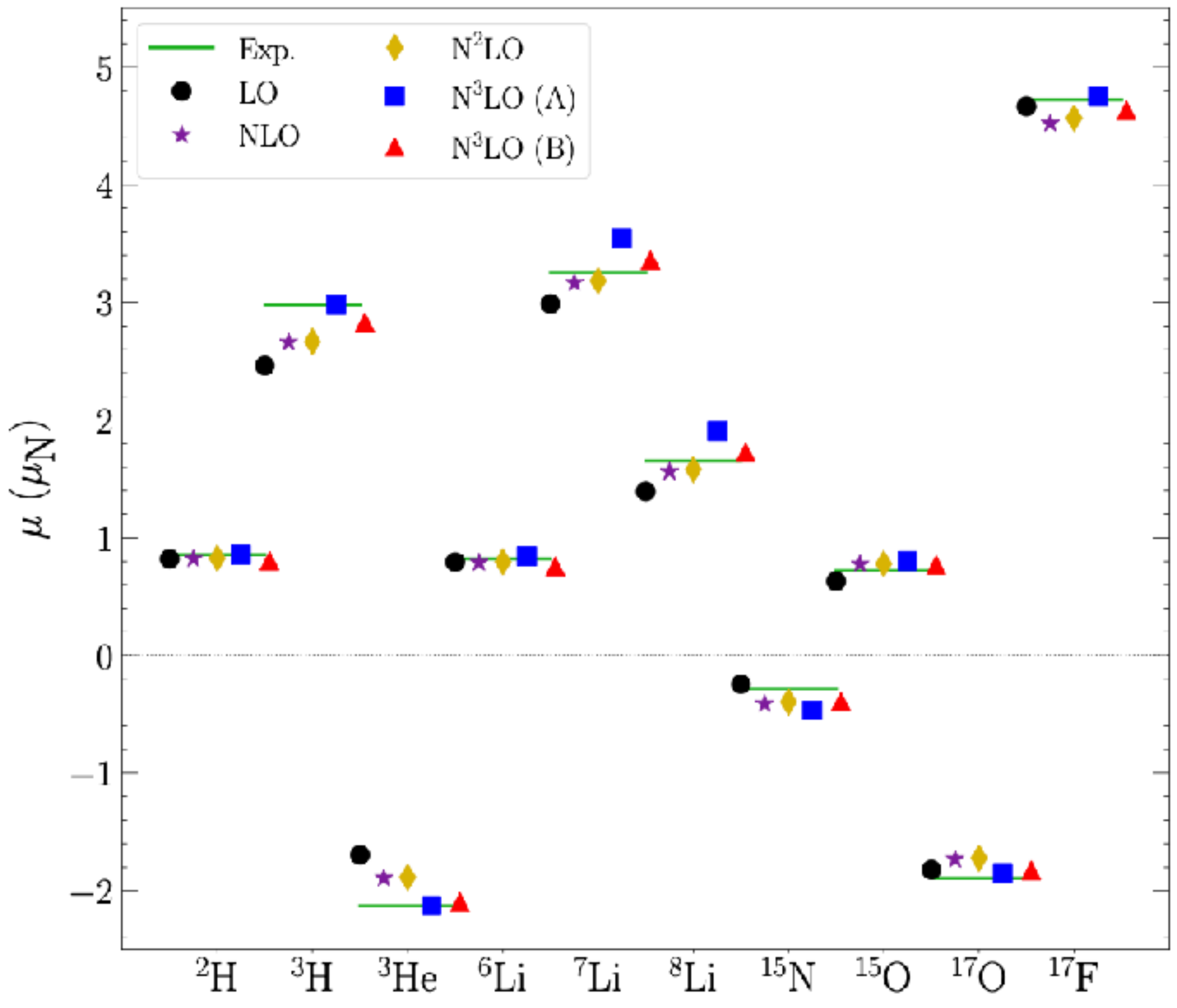
Using the magnetic moments

Δ saturation (fix d_2^V d_3^V)



[R. Schiavilla et al., PRC 99, 034005 (2019)]

Not including (d_2^V d_3^V d_2^S)



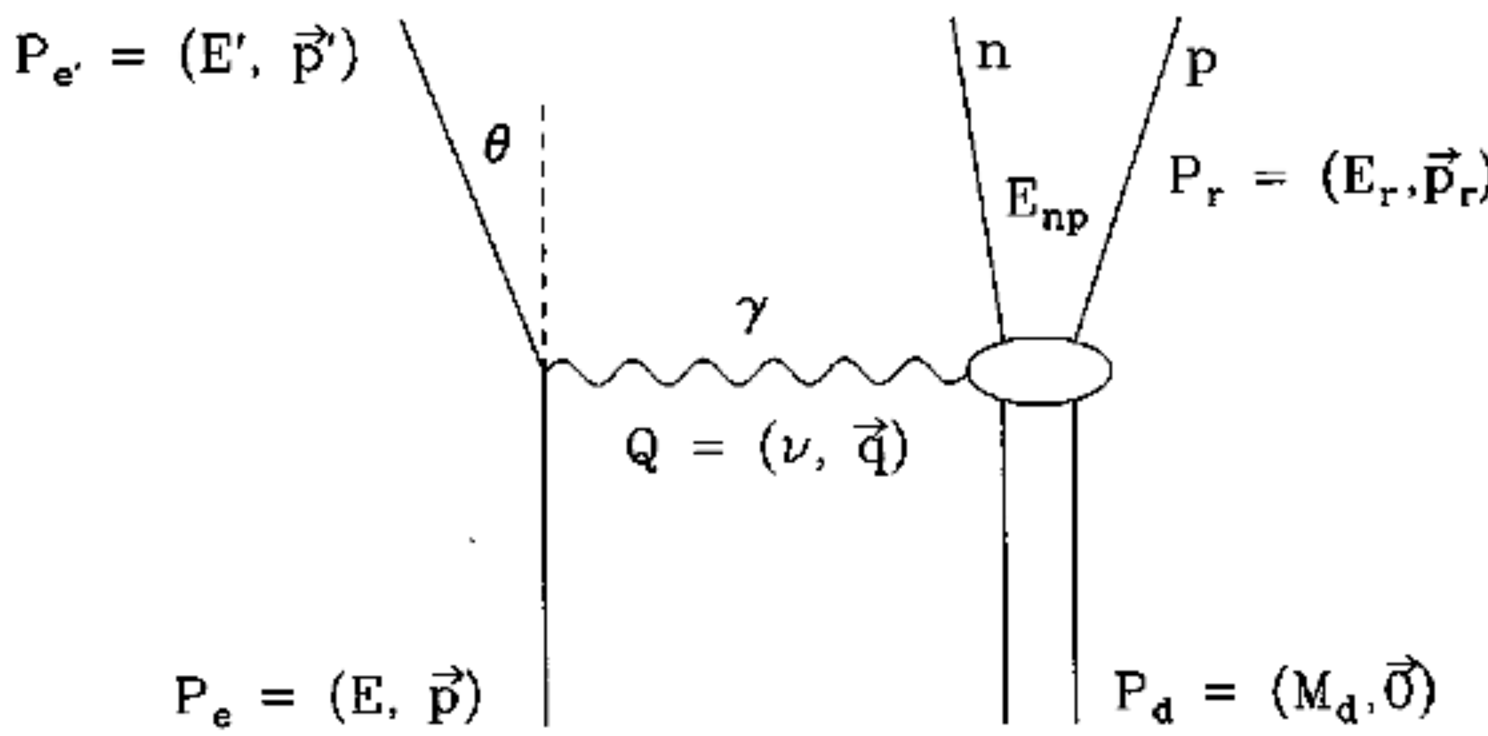
[J.D. Martin *et al.*, arXiv:2301.08349]

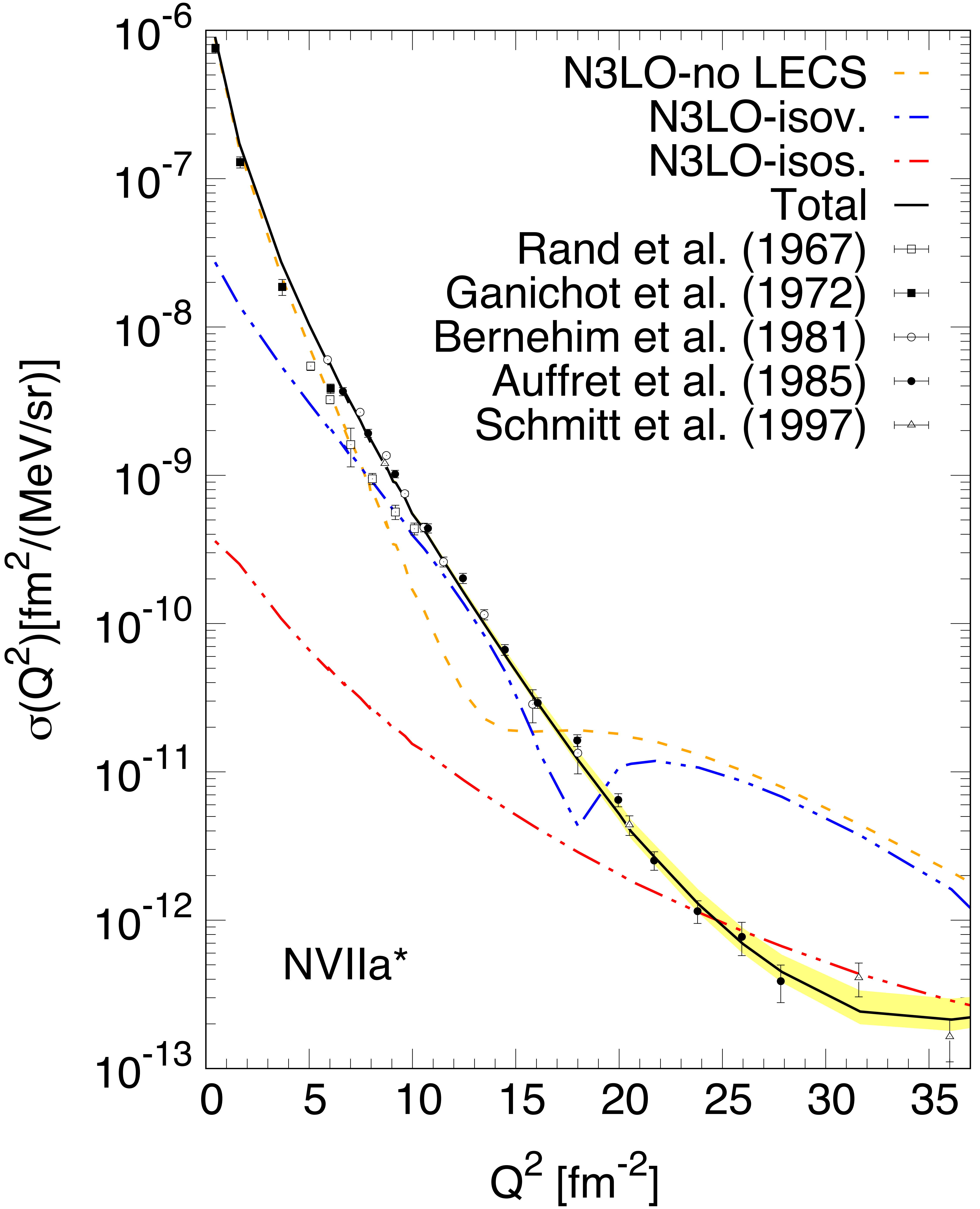
Diffraction generated by tensor forces

How to fix the LECs II

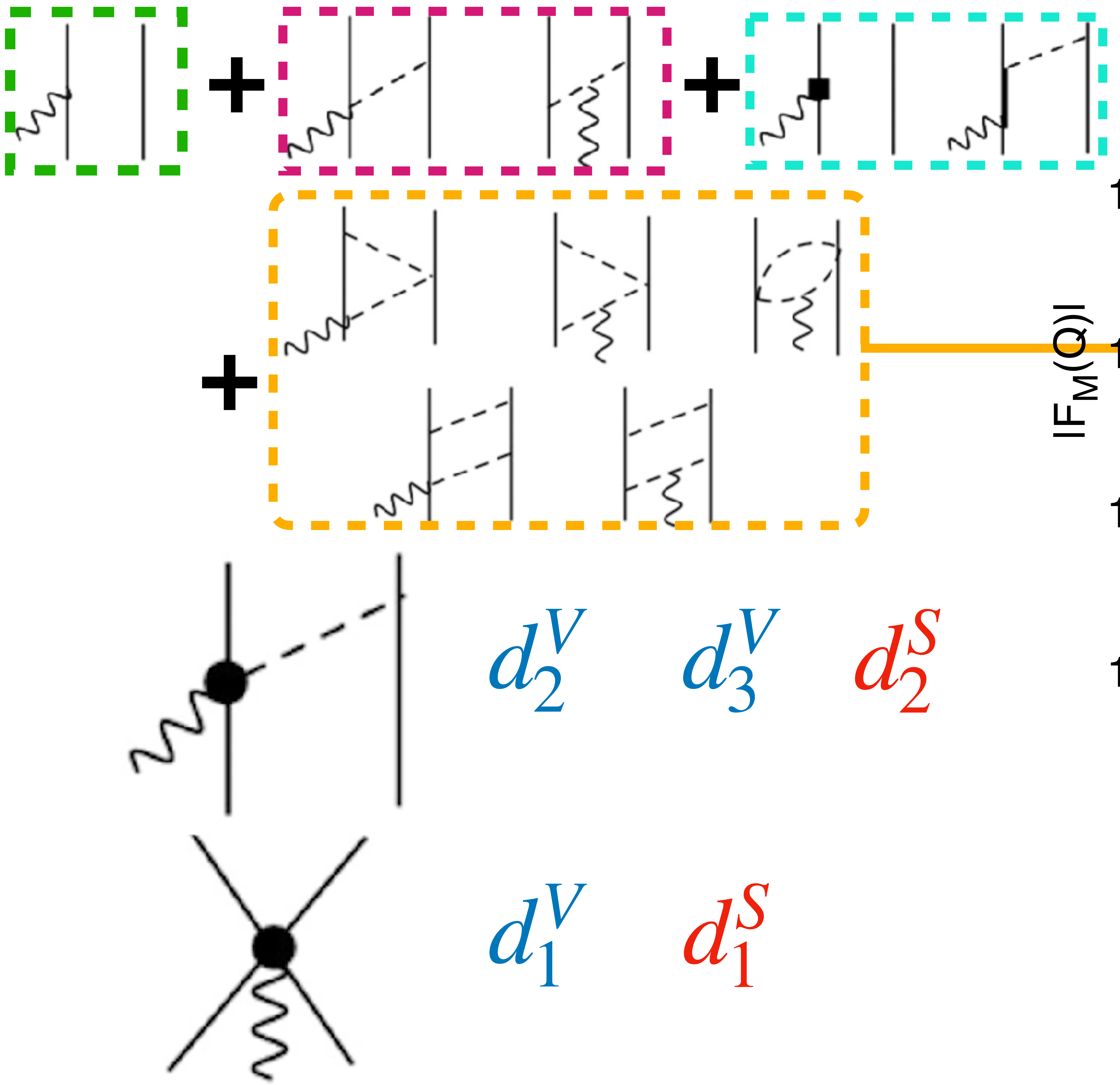
This work

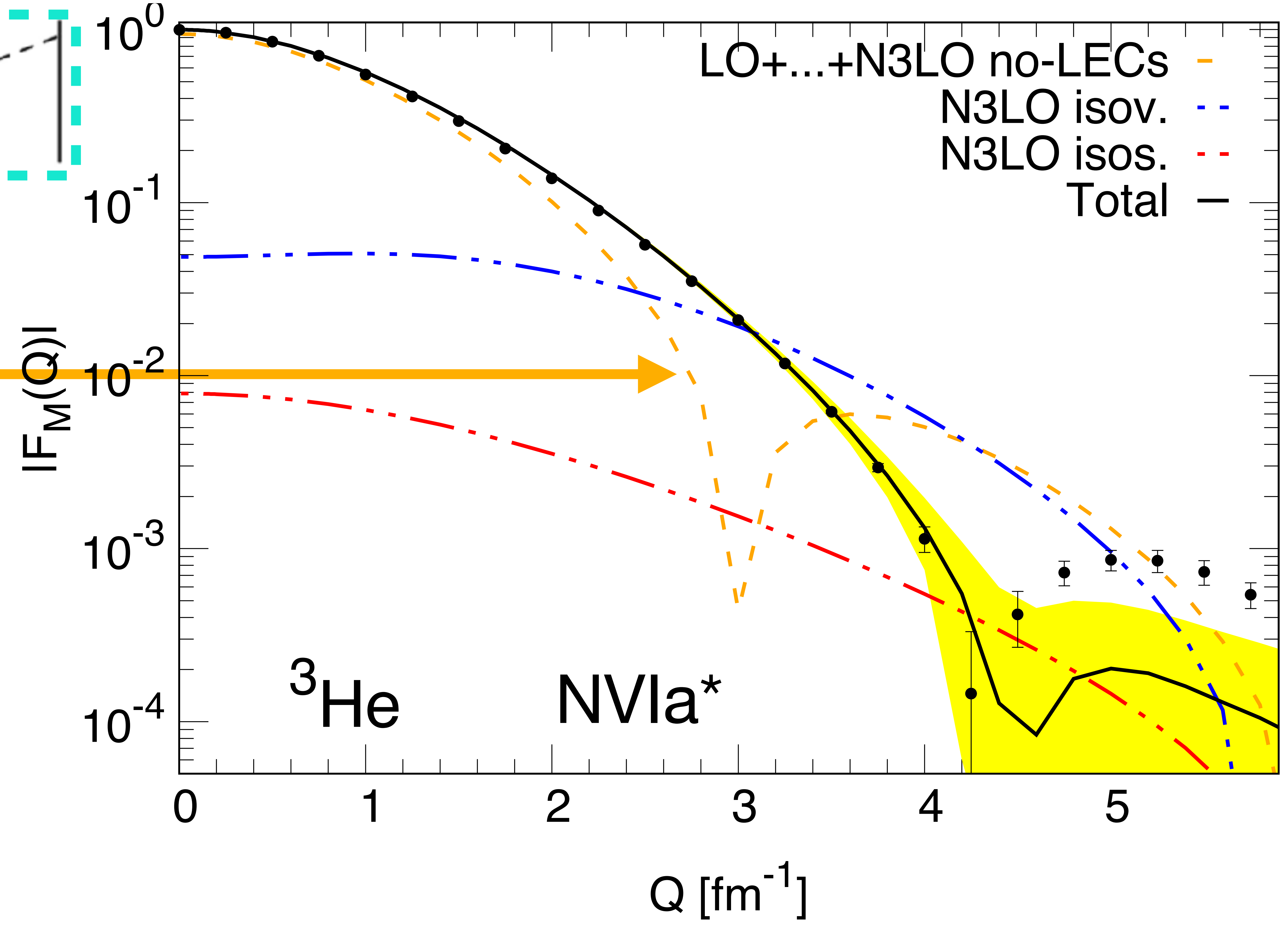
- Magnetic moments of d, ^{3}He, ^{3}H (fix normalization)
- deuteron-threshold electrodisintegration at backward angles (fix dynamics)





Prediction of A=3 Magnetic Form Factor





The isovector components fill/generates the diffraction

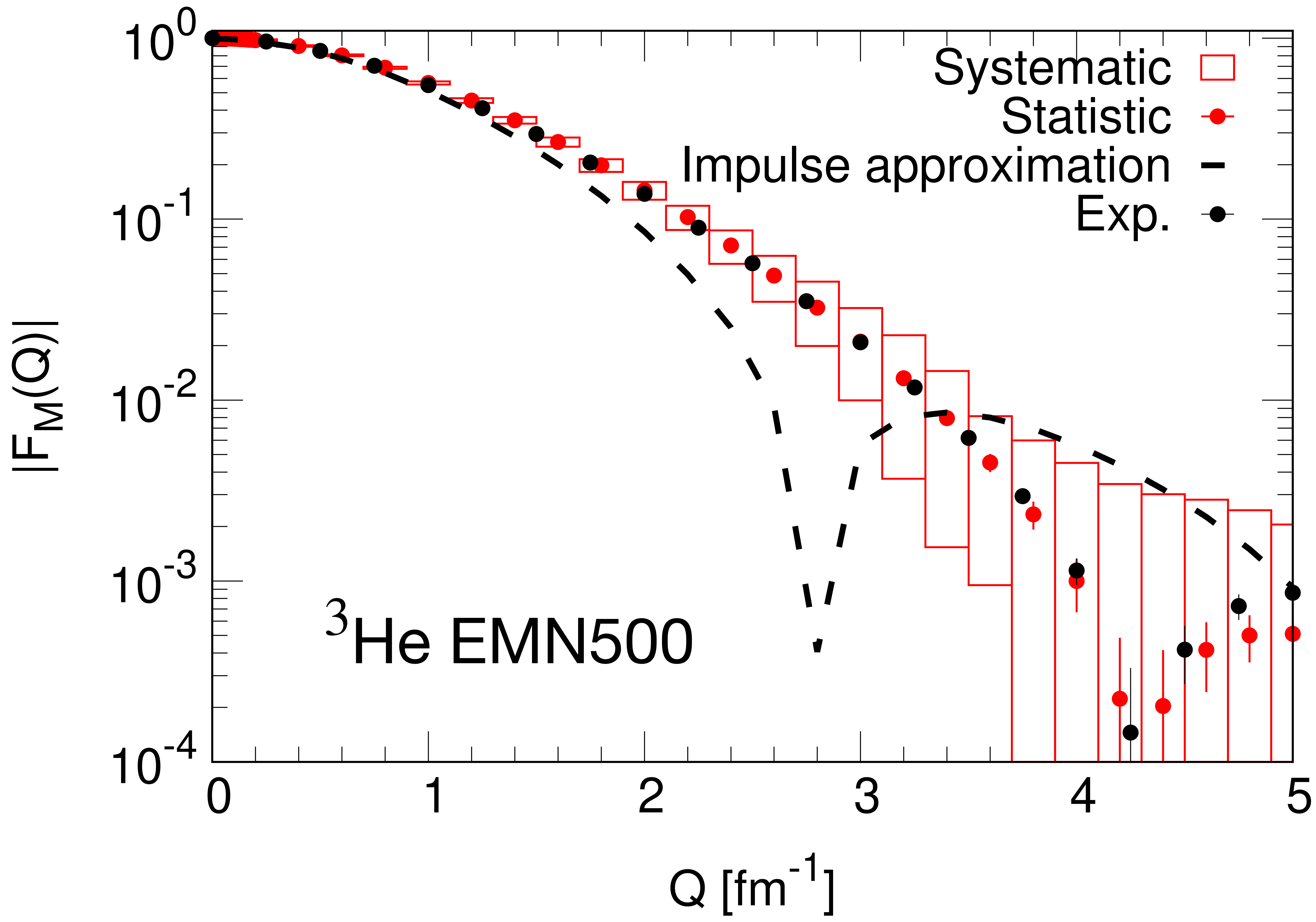
Naive truncation error estimate

Is χEFT able to describe large Q?

- Truncation errors (as [EPJA 51, 53 (2015)])

$$\alpha = \max\left\{\frac{Q}{\Lambda_b}, \frac{m_\pi}{\Lambda_b}\right\} \quad \Lambda_b = 1 \text{ GeV}$$

- Nuclear interaction + currents
- Bayesian analysis (slowly) in progress
- Is Q the right scale for this process?



Reliability of the predictions

Is χEFT able to describe large Q?

- Truncation errors (as [EPJA 51, 53 (2015)])

$$\alpha = \max\left\{\frac{Q}{\Lambda_b}, \frac{m_\pi}{\Lambda_b}\right\} \quad \Lambda_b = 1\ \text{GeV}$$

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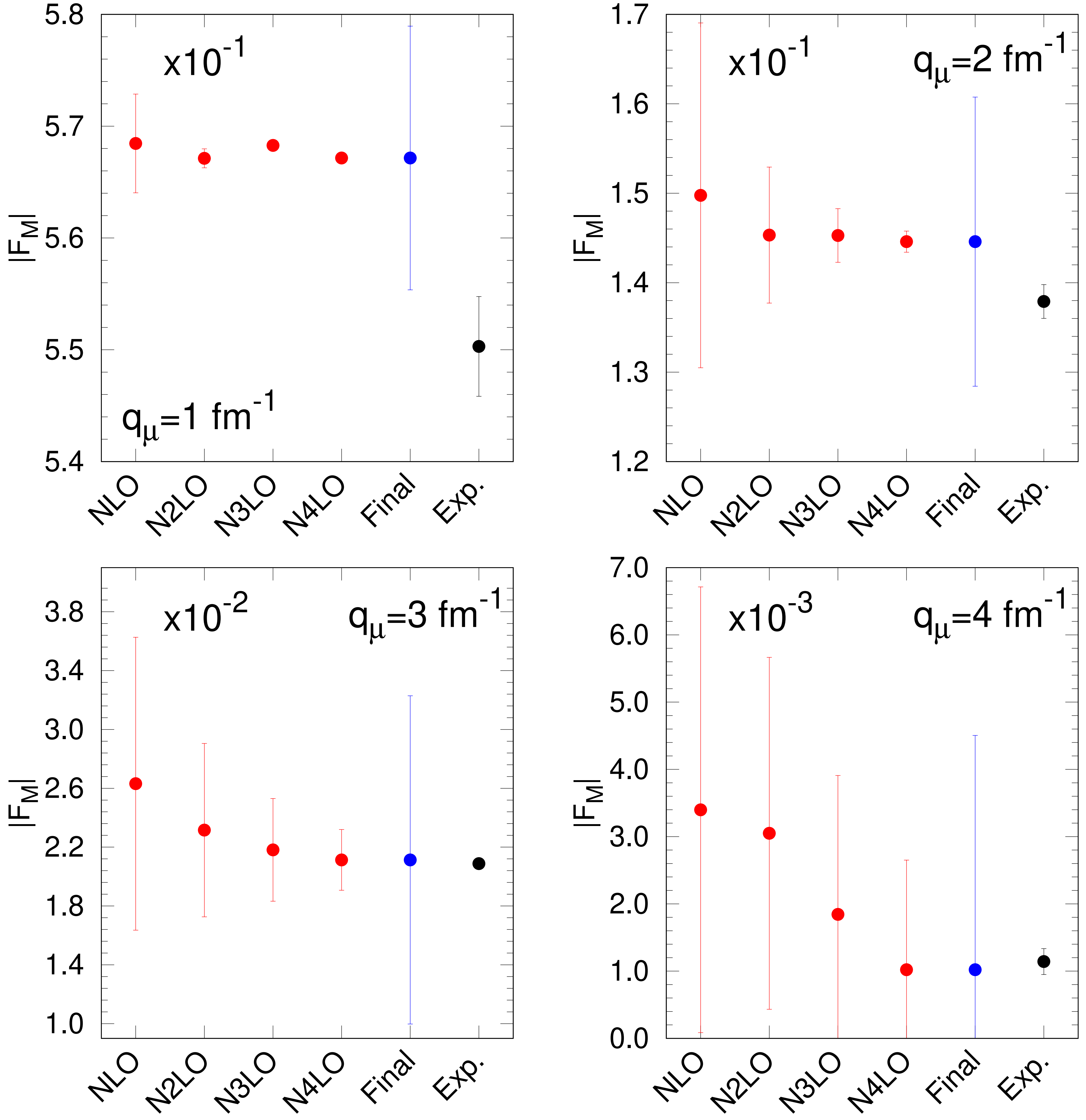
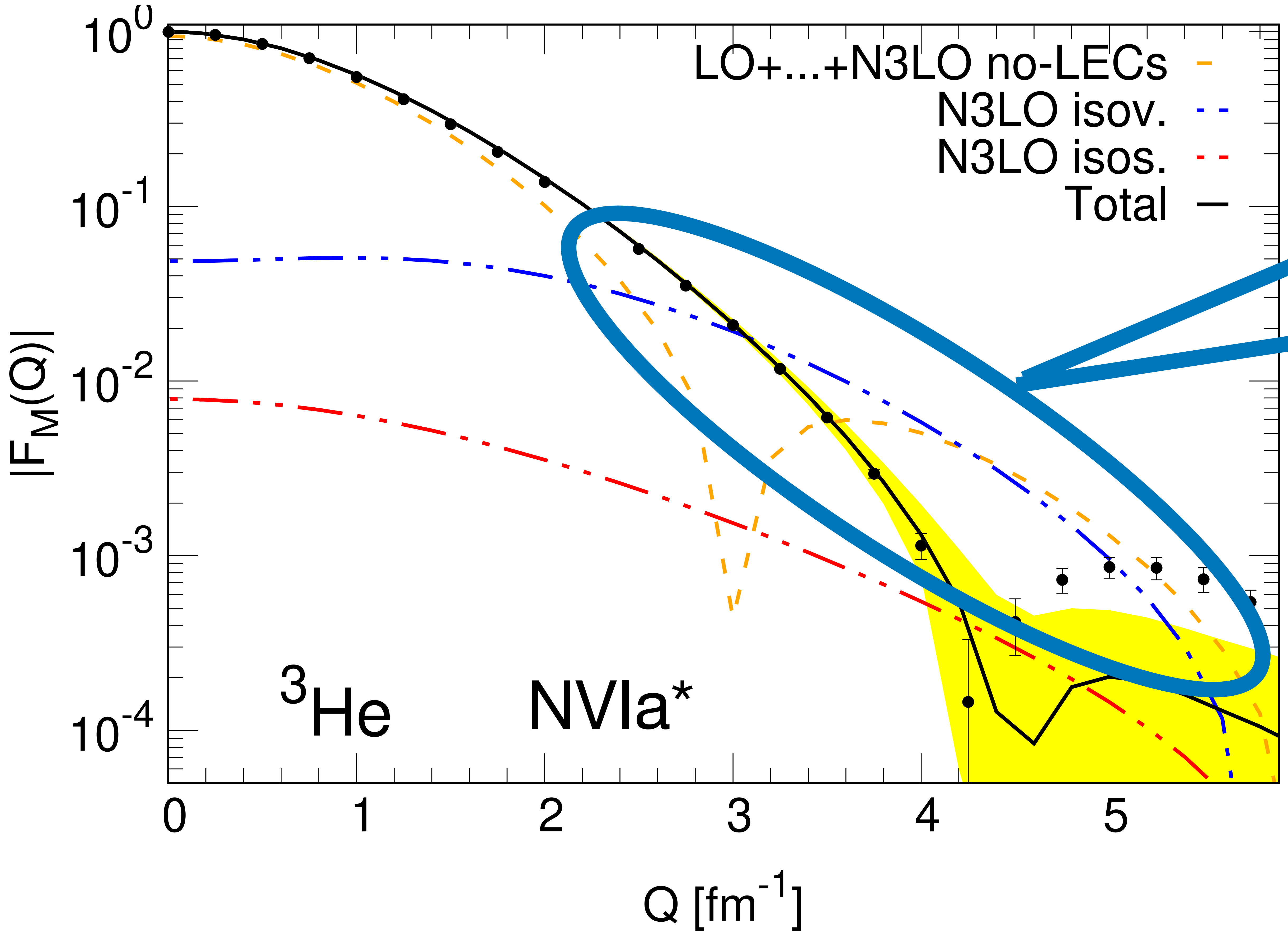


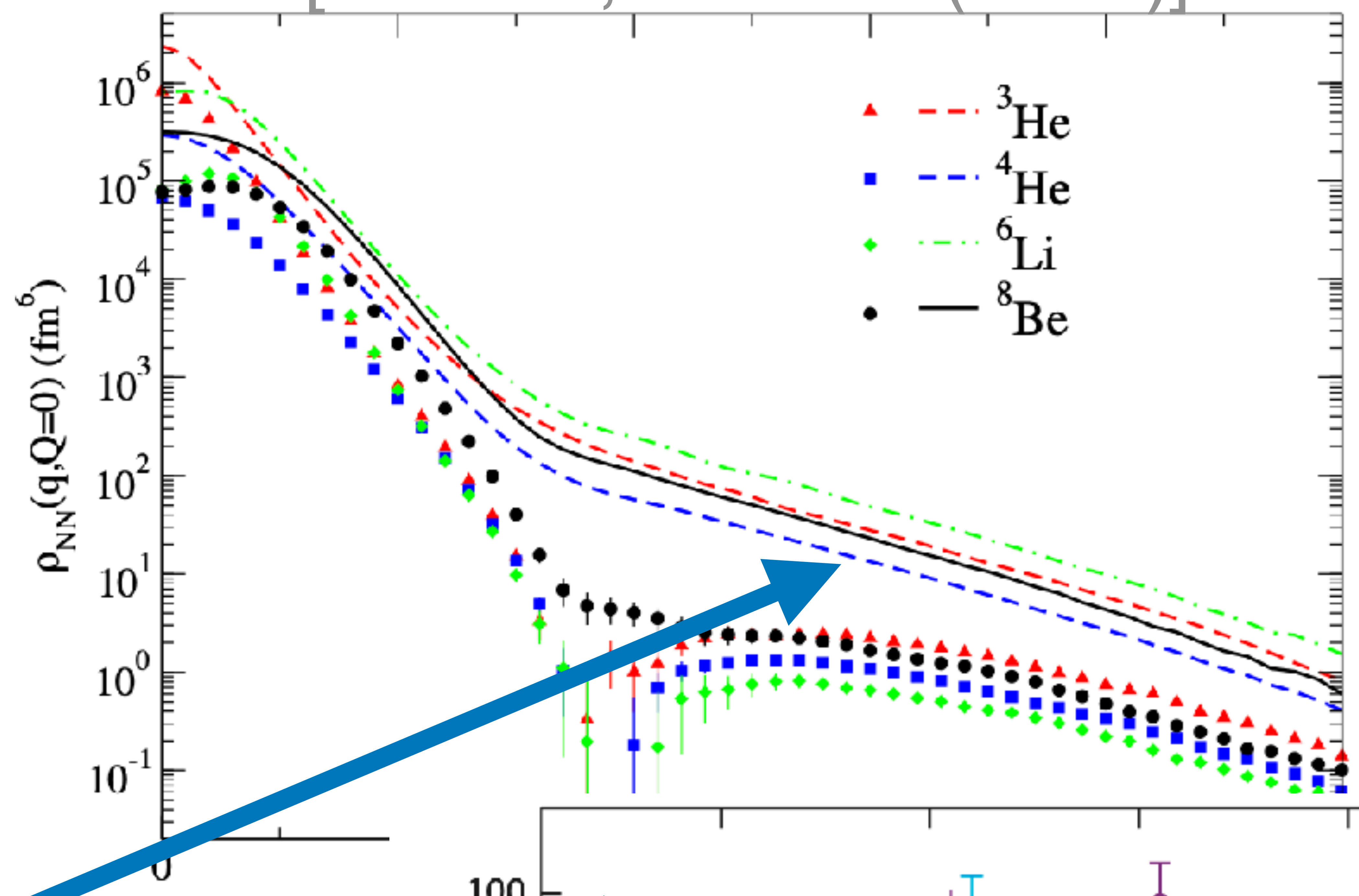
^{3}He EMN500

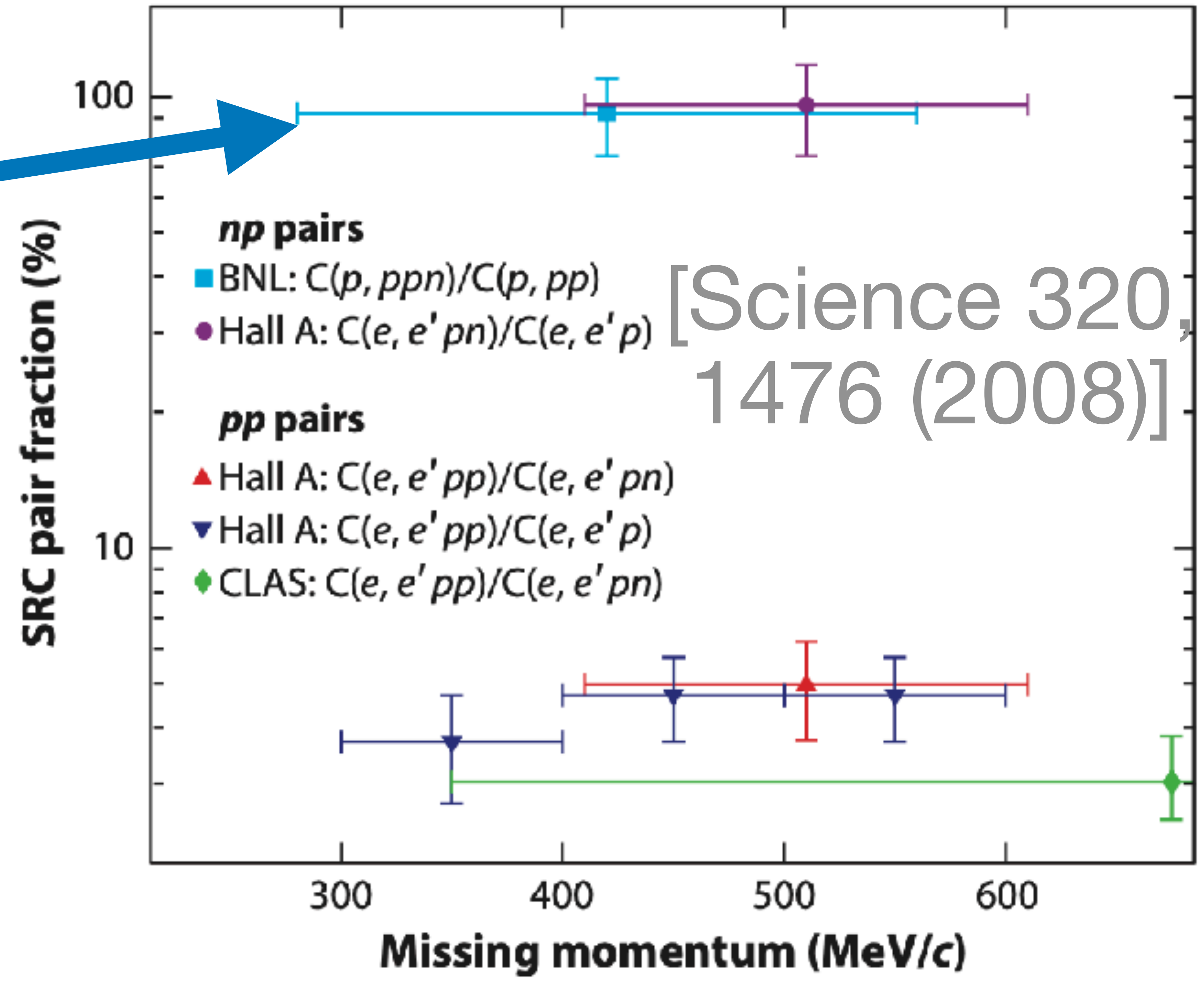
Why does it work?

Isovector currents transform S/T=0/1 in S/T=1/0 pairs

np dominance





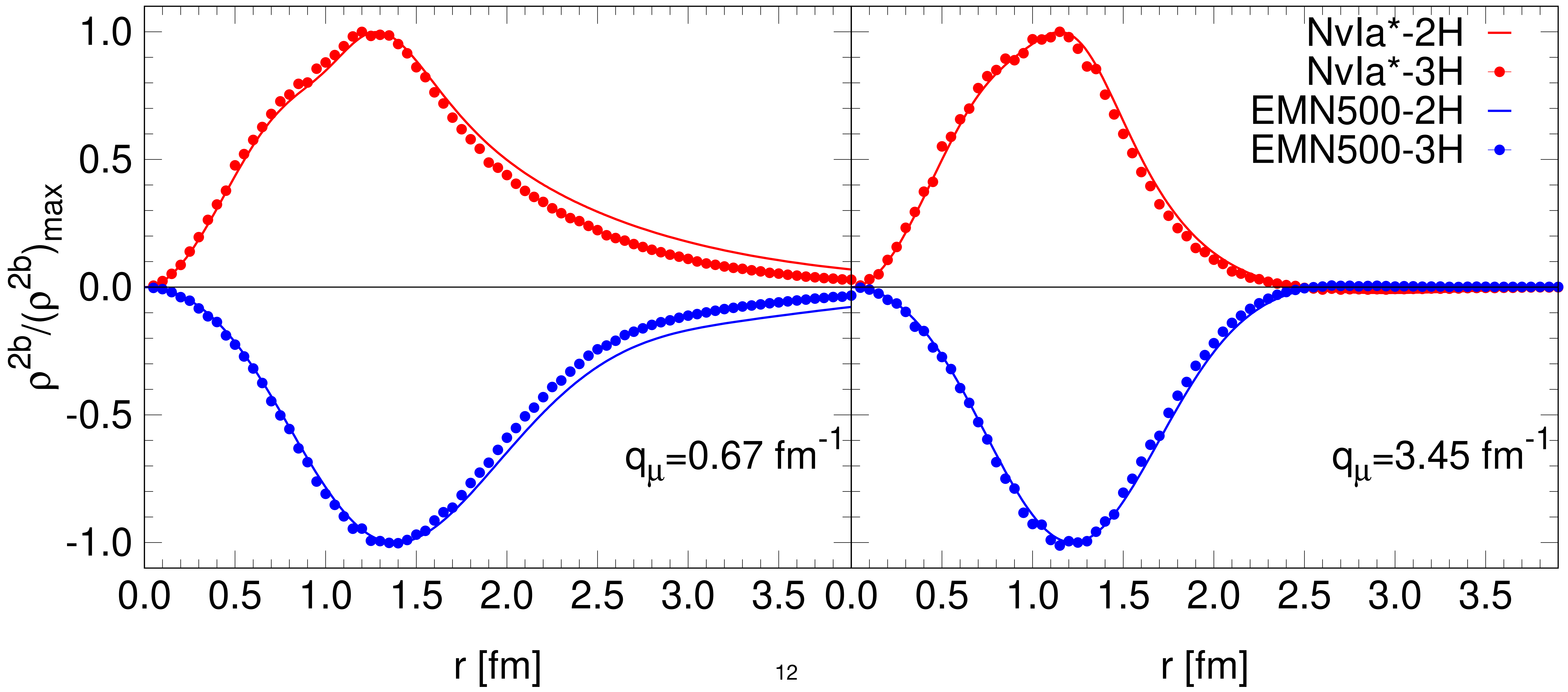


[Science 320, 1476 (2008)]

Why does it work?

Universal behavior of isovector transitions

Correlated np pairs ⟷ **Universal 2-body wave functions** ⟷ **Universal 2-body transition densities**

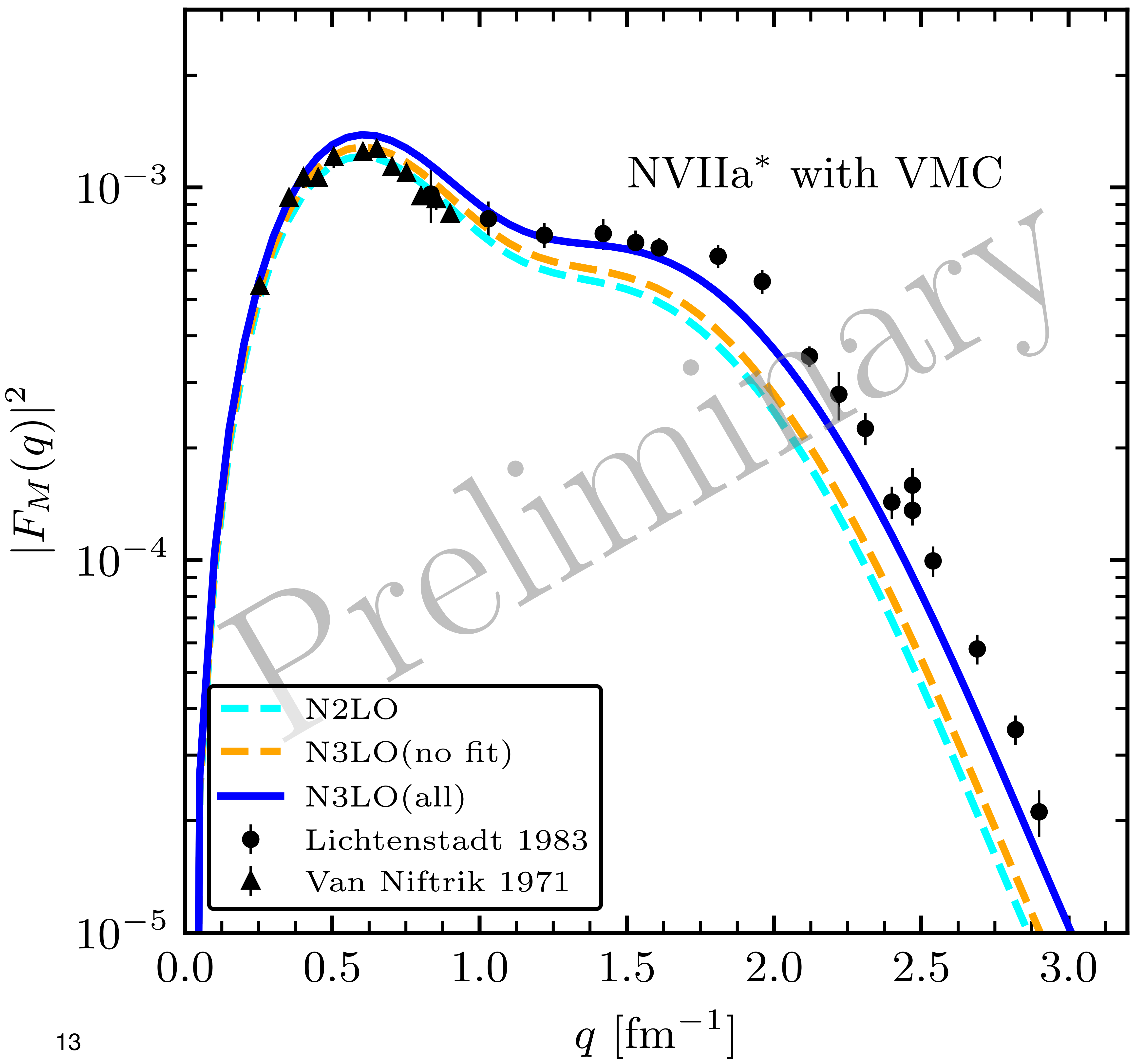


Beyond few-body

Parameter free prediction of ^{7}Li MFF

ft. QMC@WASHU
C.W. Graham, G.B. King,
S. Pastore, M. Piarulli

- No free parameters (we reproduce also the magnetic moments)
- Fitted terms plays a role for Q>0.3 GeV for larger systems
- Data for more nuclei would permit more constraining test
- Prediction up to A<11 with VMC and GFMC in progress



Part II

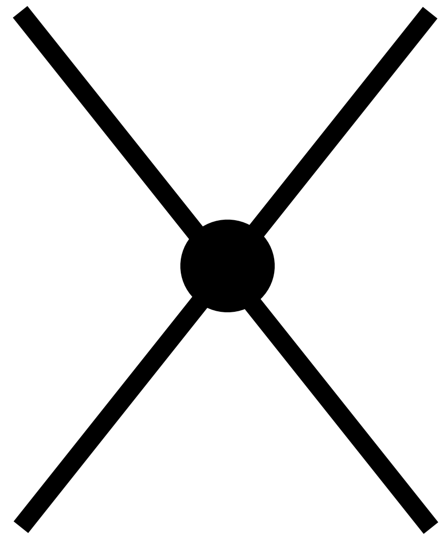
with B. Fore and A. Lovato

To the essential

Pionless EFT model [R. Schiavilla et al. Phys. Rev. C 103, 054003 (2021)]

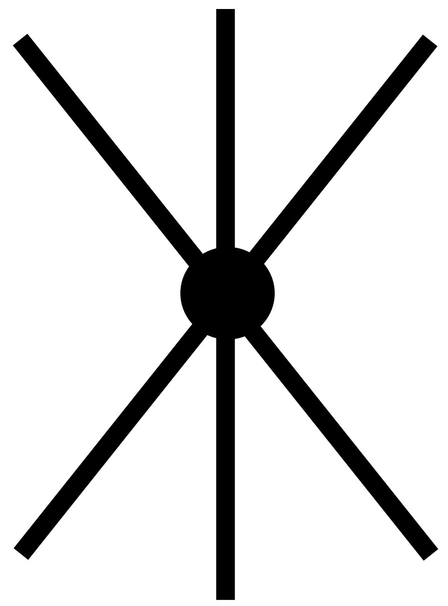
- Two-body interactions (with optimized cut-off — model “o”)

$$V = C_{01} P_0^\sigma P_1^\tau + C_{10} P_1^\sigma P_0^\tau$$



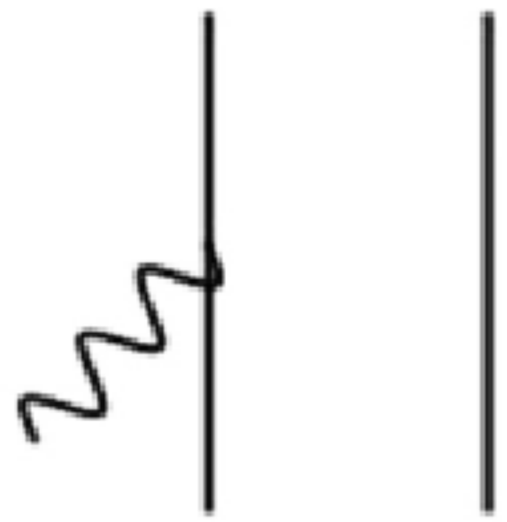
- Three-body interaction ($R_3 = 1.1$ fm)

$$V_{3b} = c_E \frac{f_\pi^4}{\Lambda_\chi} \frac{(\hbar c)^6}{\pi^3 R_3^6} \sum_{\text{cyclic } ijk} e^{-\left(r_{ij}^2 + r_{jk}^2\right)/R_3^2}$$



- Magnetic moment operator

$$\mu_z = \frac{1+\tau_z}{2} L_z + \frac{\mu_s + \mu_v \tau_z}{2} \sigma_z$$



Neural-Network Quantum States

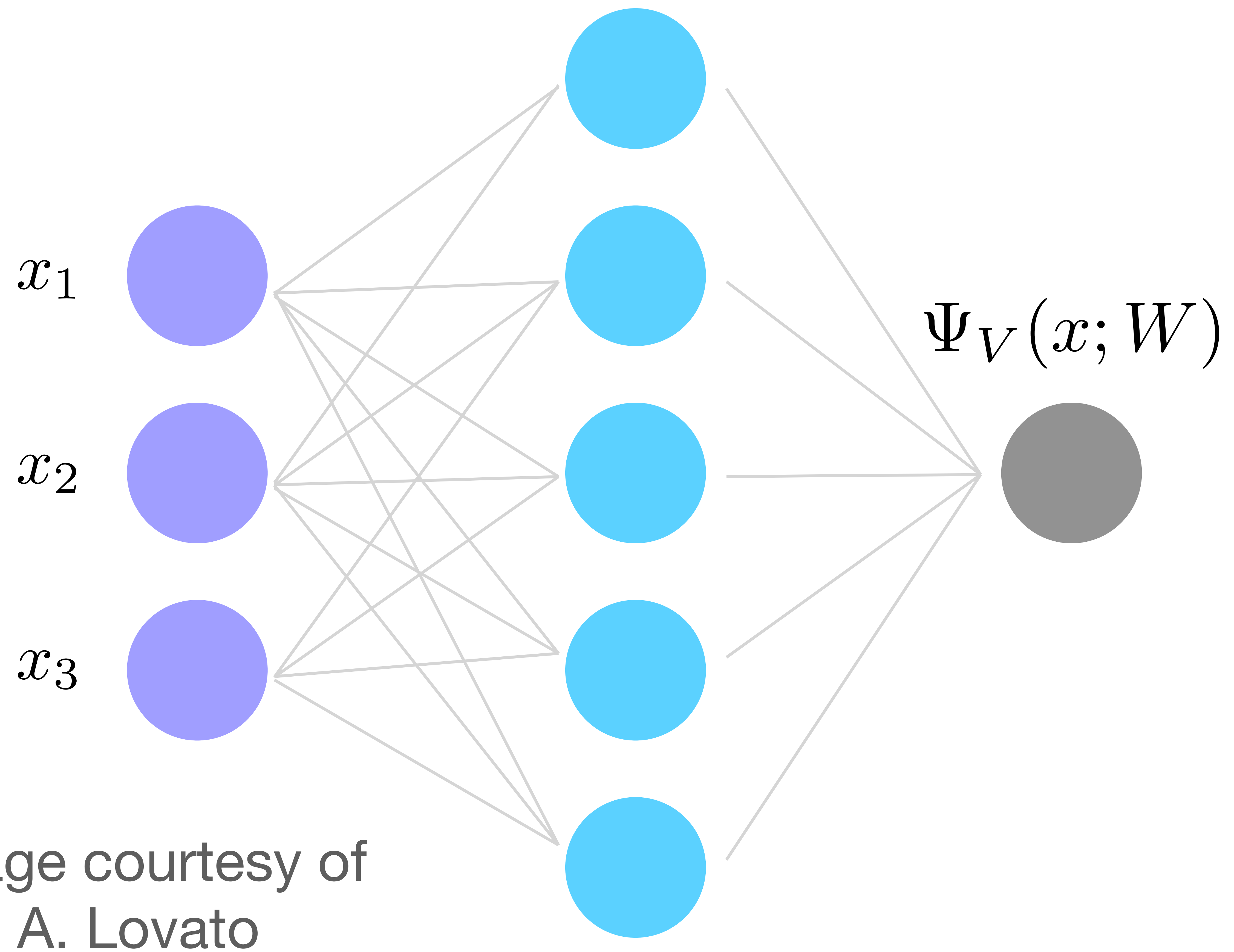
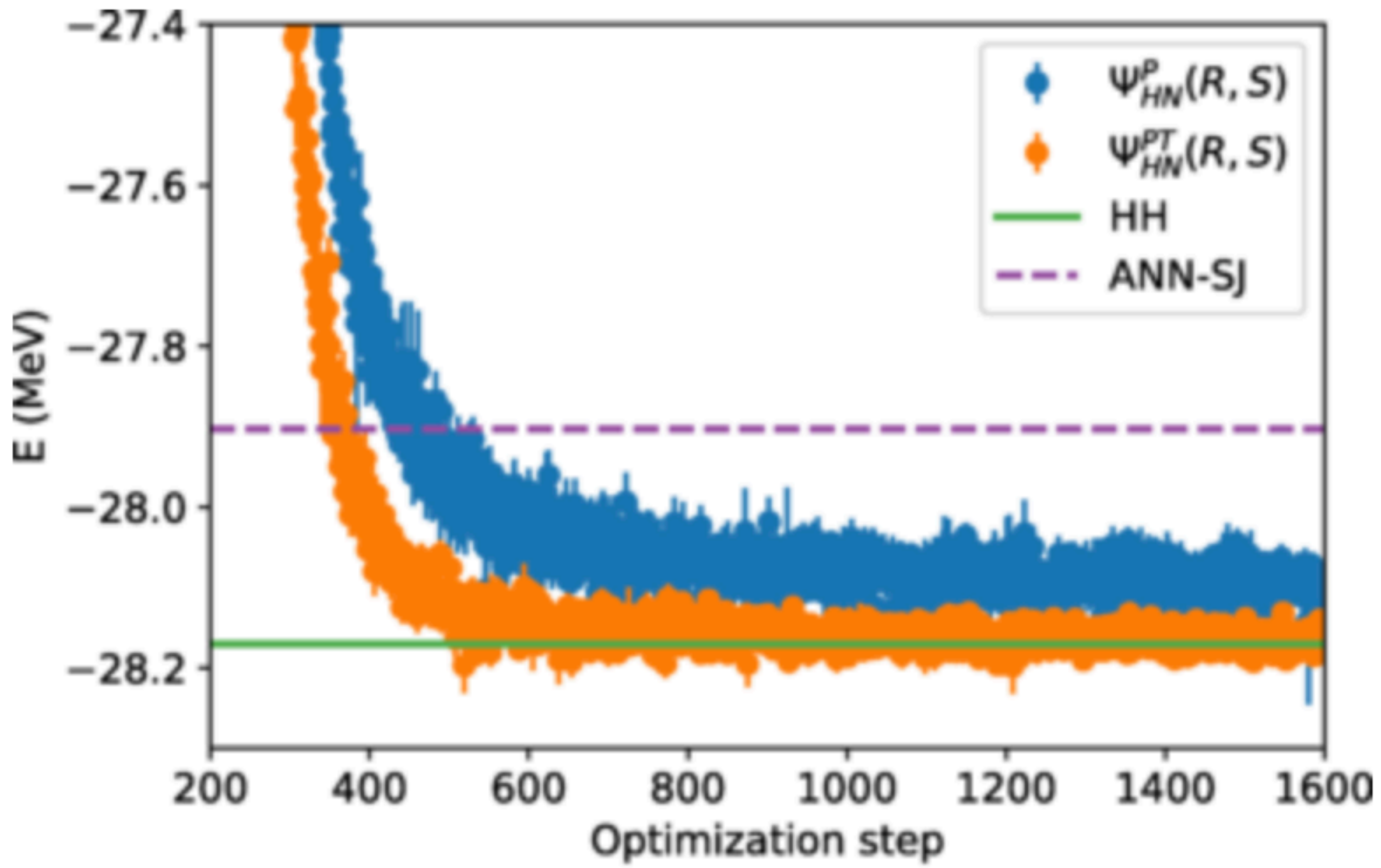


Image courtesy of A. Lovato

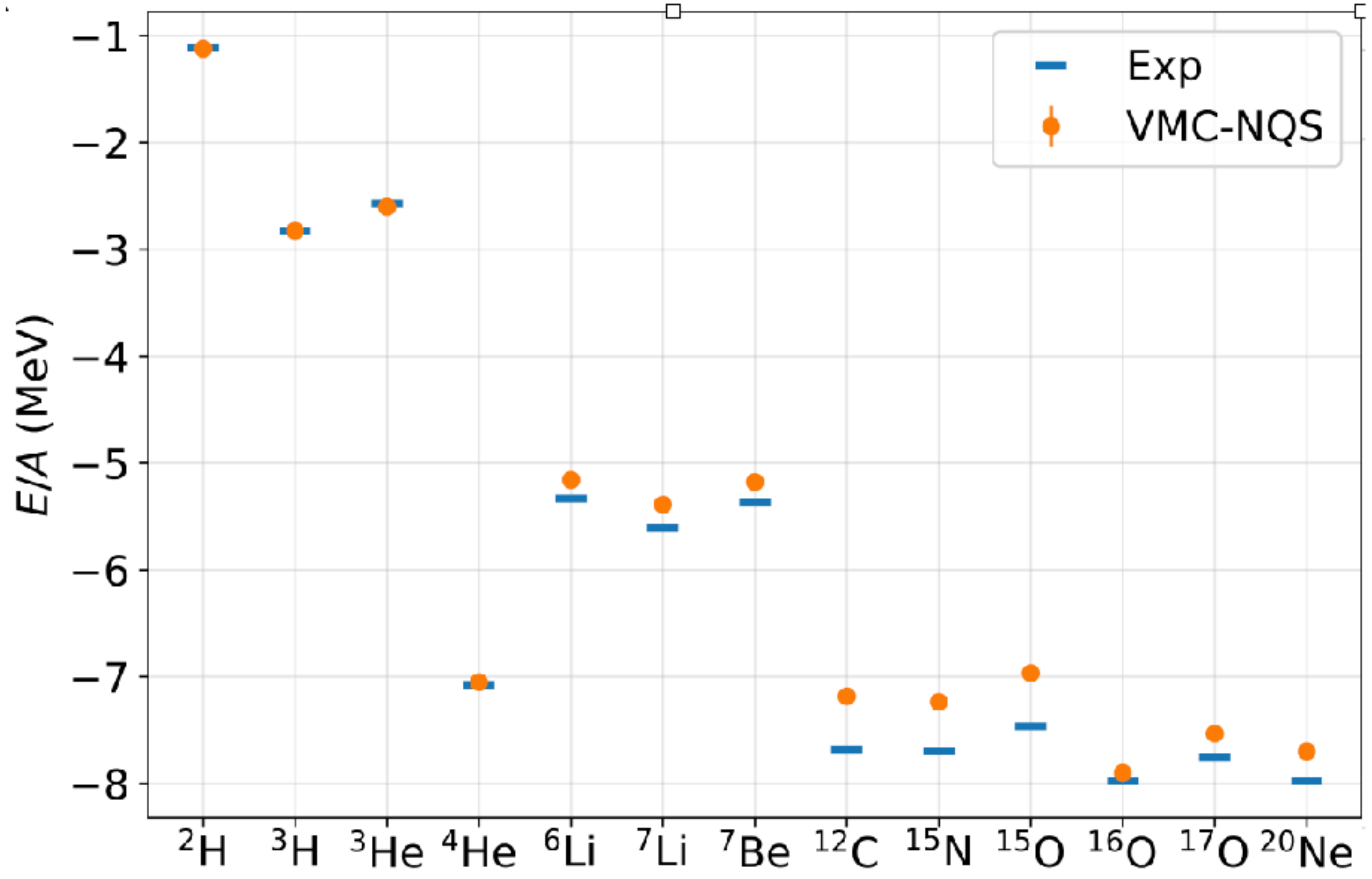
$$E = \min_W \frac{\langle \Psi_V(W) | H | \Psi_V(W) \rangle}{\langle \Psi_V(W) | \Psi_V(W) \rangle}$$

VMC + Stochastic Reconfiguration



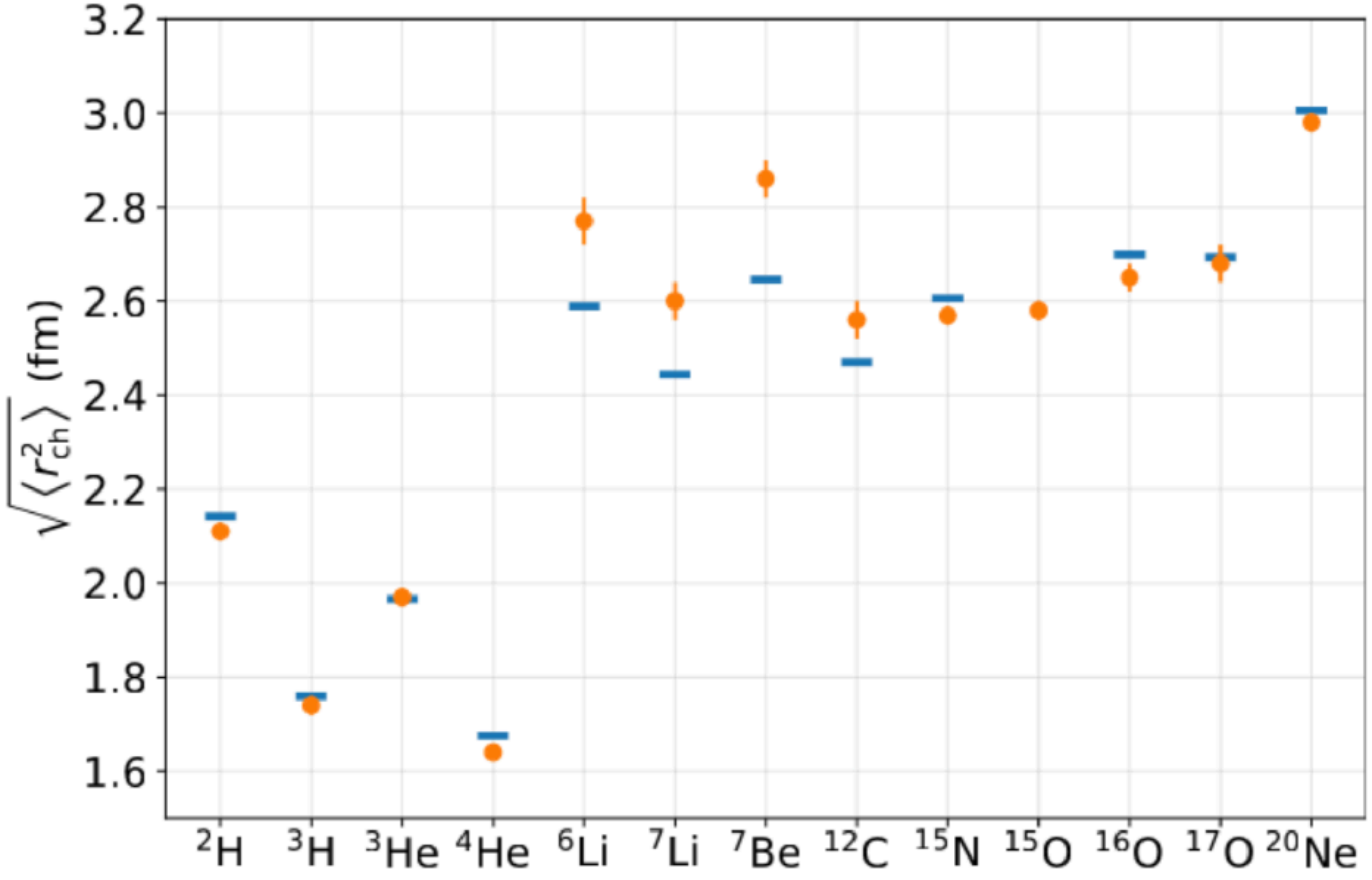
A. Lovato, et al., Phys. Rev. Res. ***4****, 043178 (2022)*

Binding energies and charge radii



Good agreement with the experimental values!!

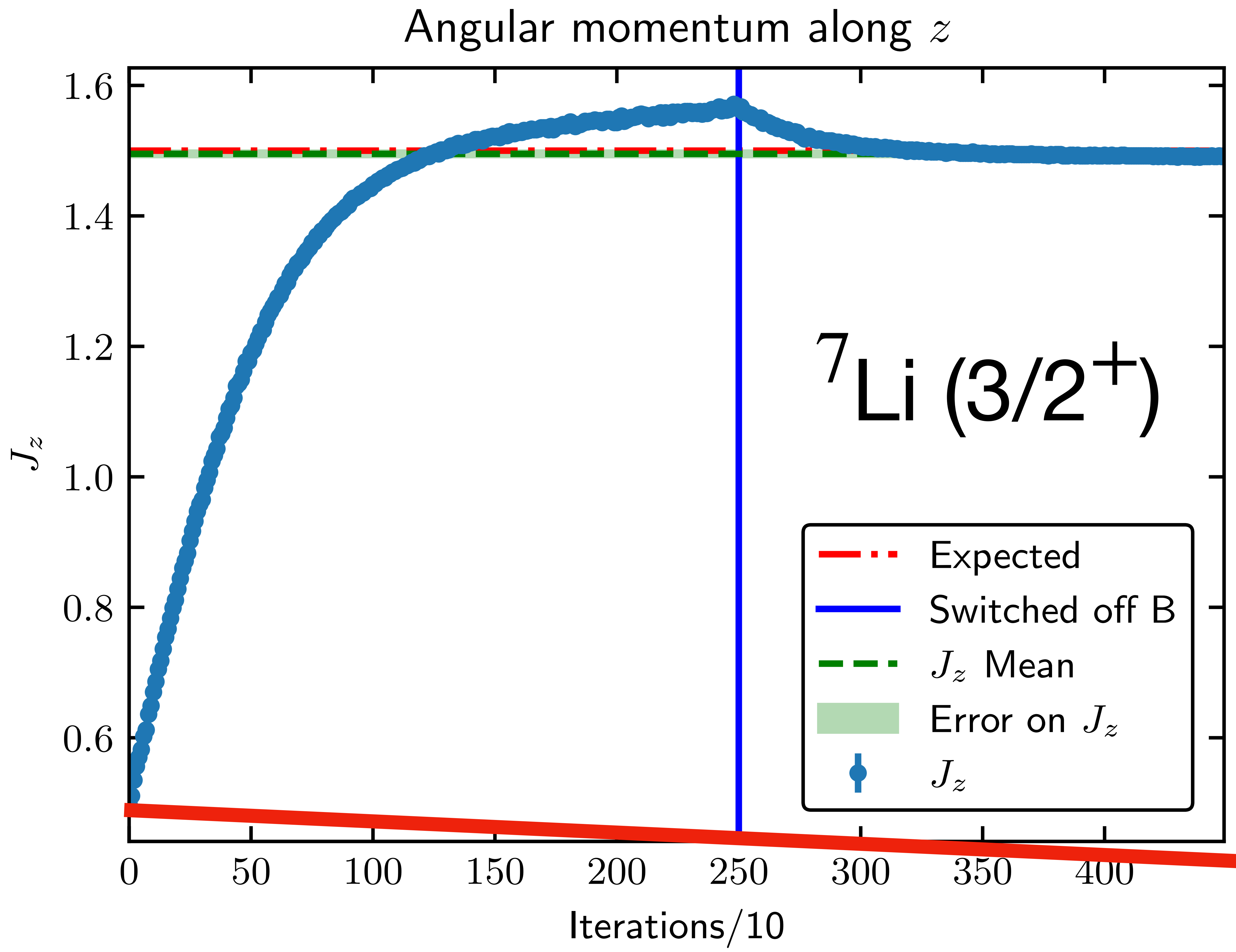
^{6}He, ^{8}Li, ^{8}B, ^{9}C, ^{17}F are unstable against cluster breakup

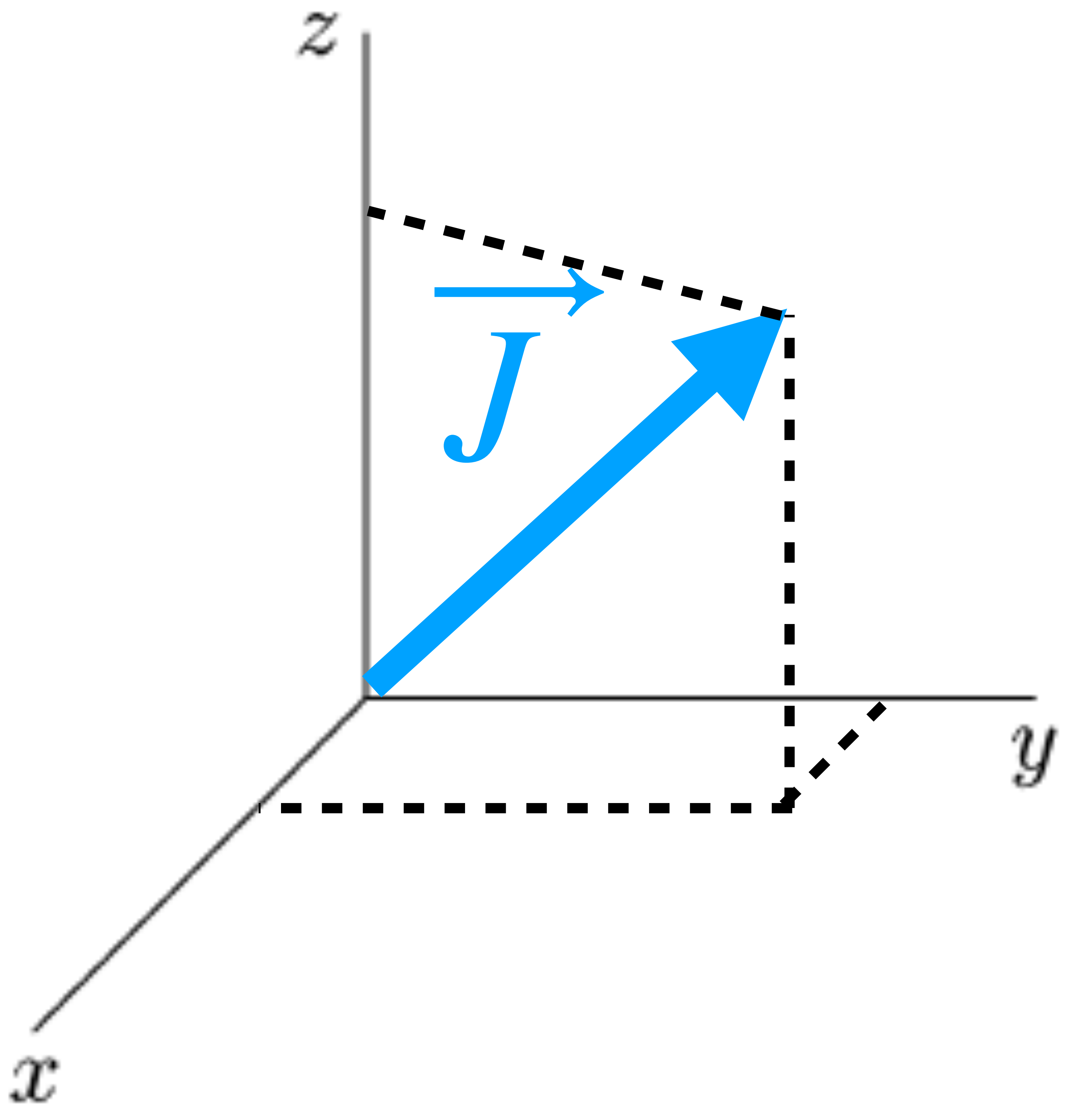


Projection of NQS

What is measured

$$\mu = \langle J, J_z = J | \mu_z | J, J_z = J \rangle$$



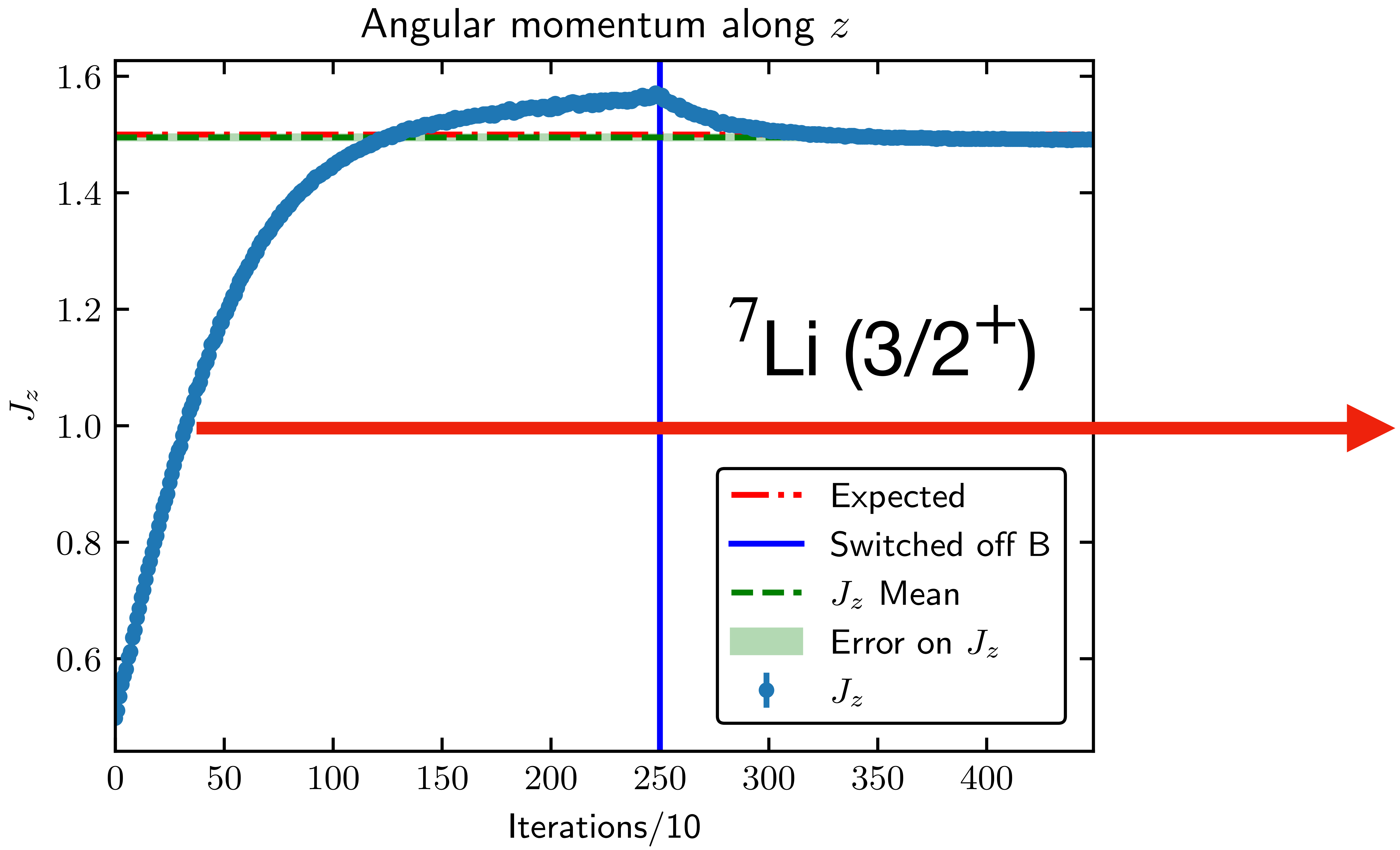


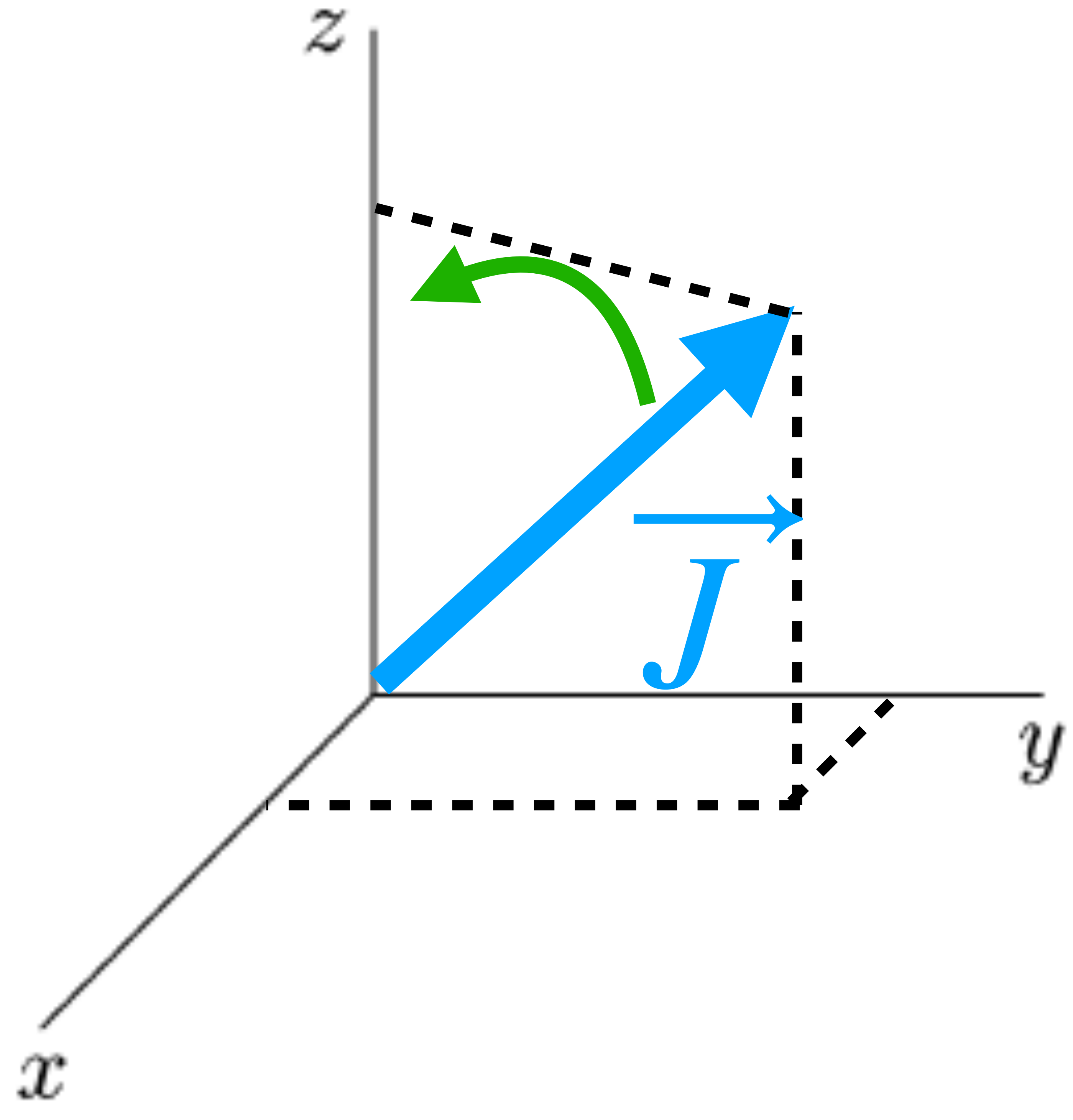
$$|\Psi_J\rangle = \sum_{J_z} c_{J_z} |\Psi_{J,J_z}\rangle$$

Projection of NQS

What is measured

$$\mu = \langle J, J_z = J | \mu_z | J, J_z = J \rangle$$



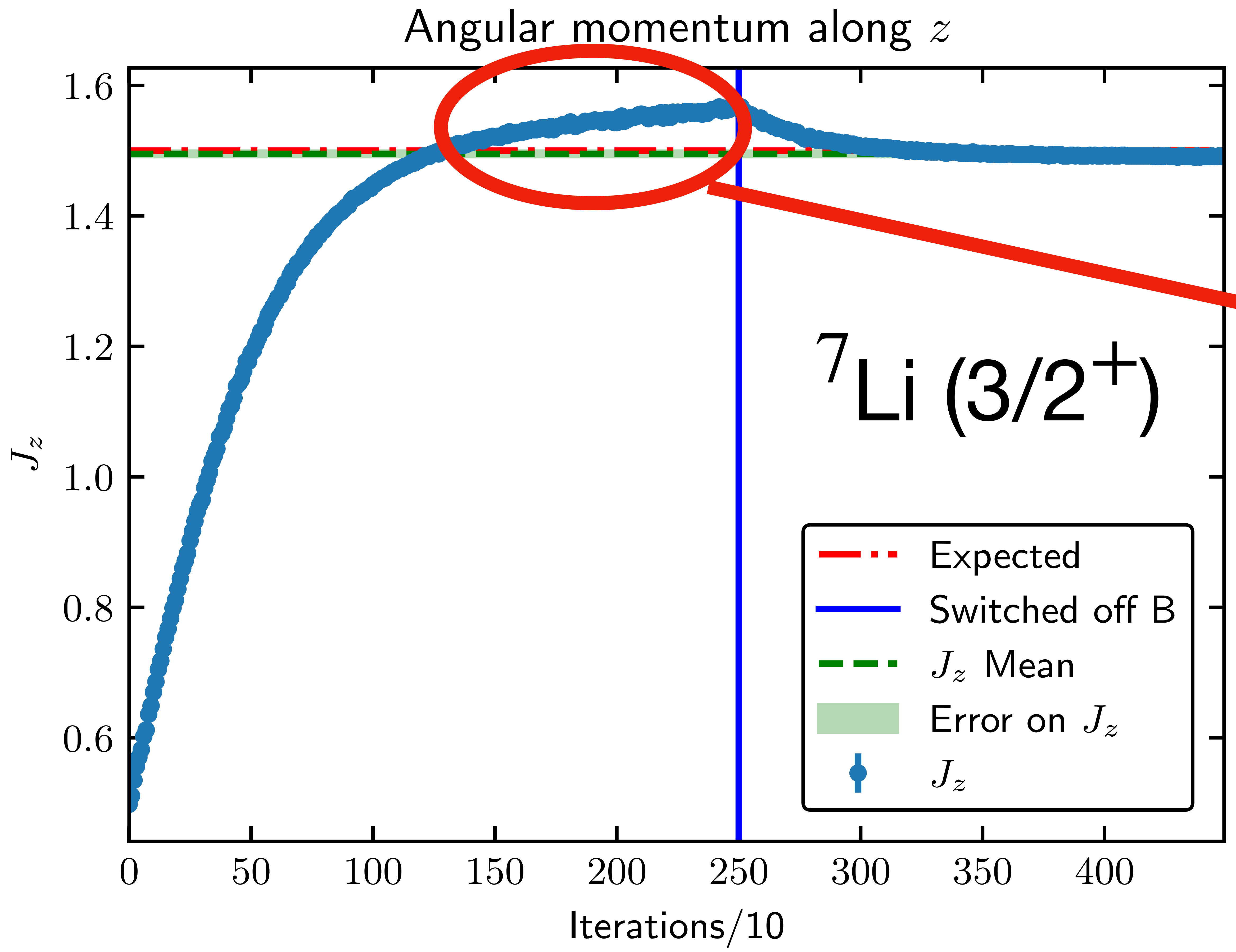


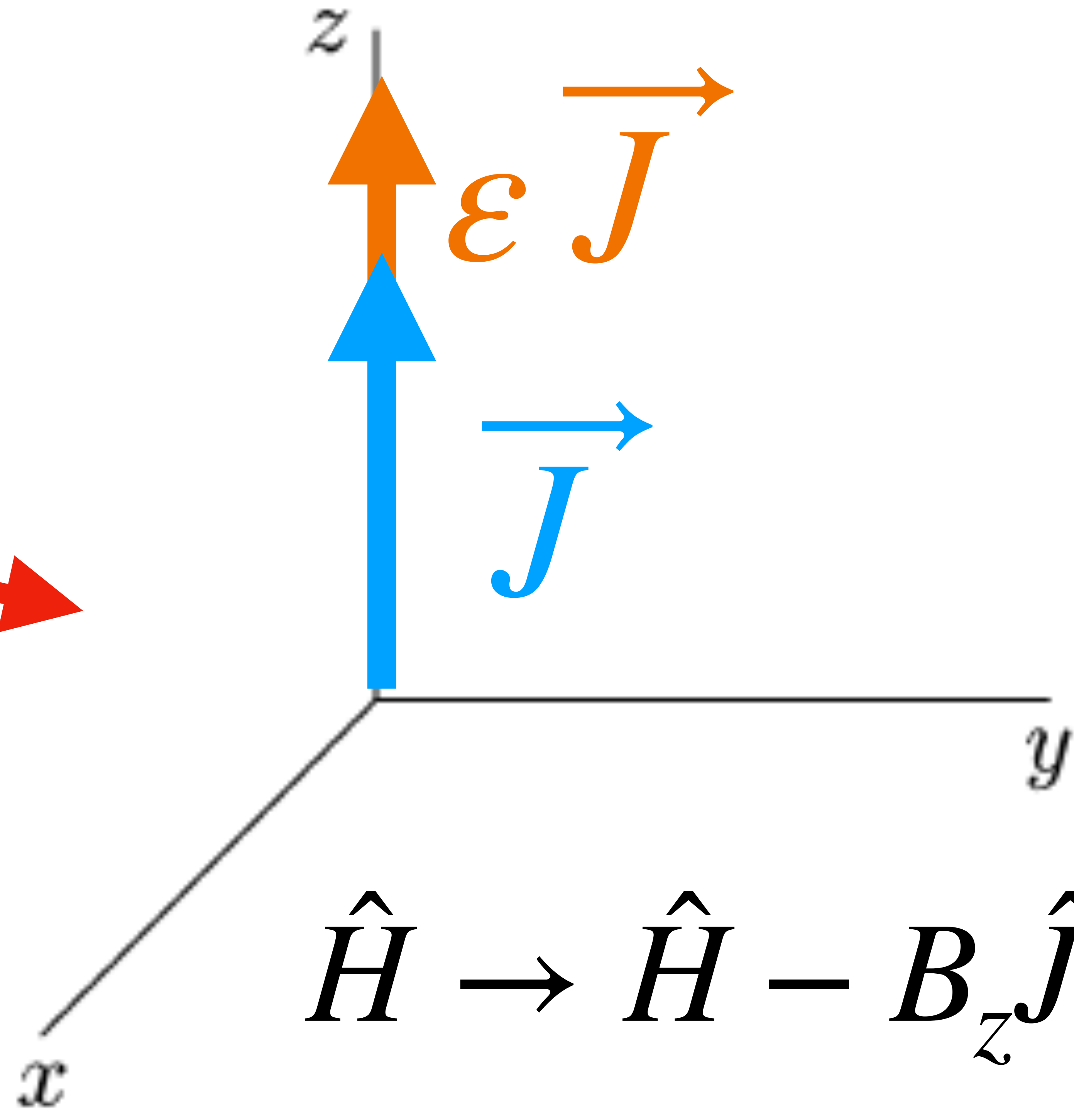
$$\hat{H} \to \hat{H} - B_z \hat{J}_z$$

Projection of NQS

What is measured

$$\mu = \langle J, J_z = J | \mu_z | J, J_z = J \rangle$$

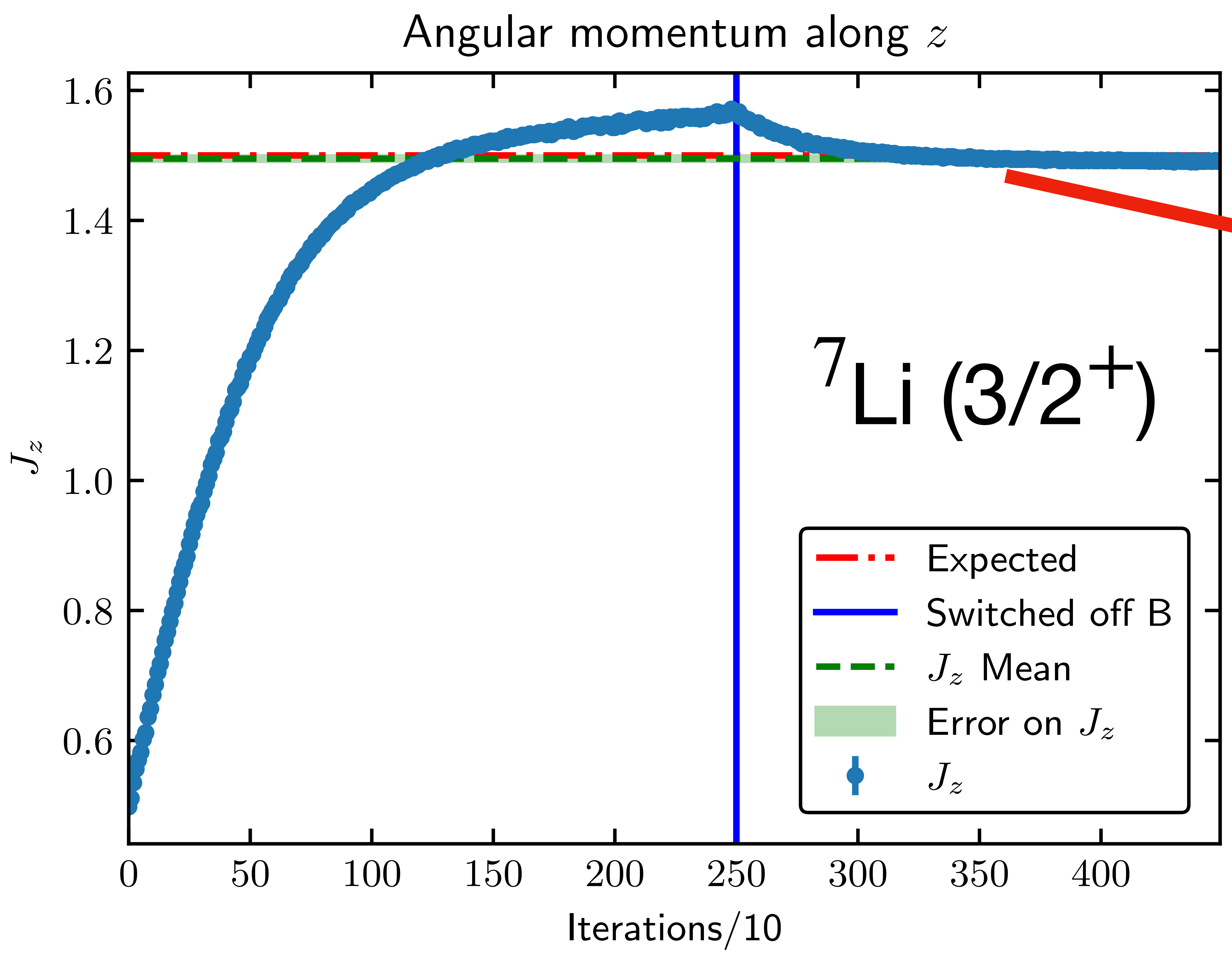




$$\hat{H} \rightarrow \hat{H} - B_z \hat{J}_z$$

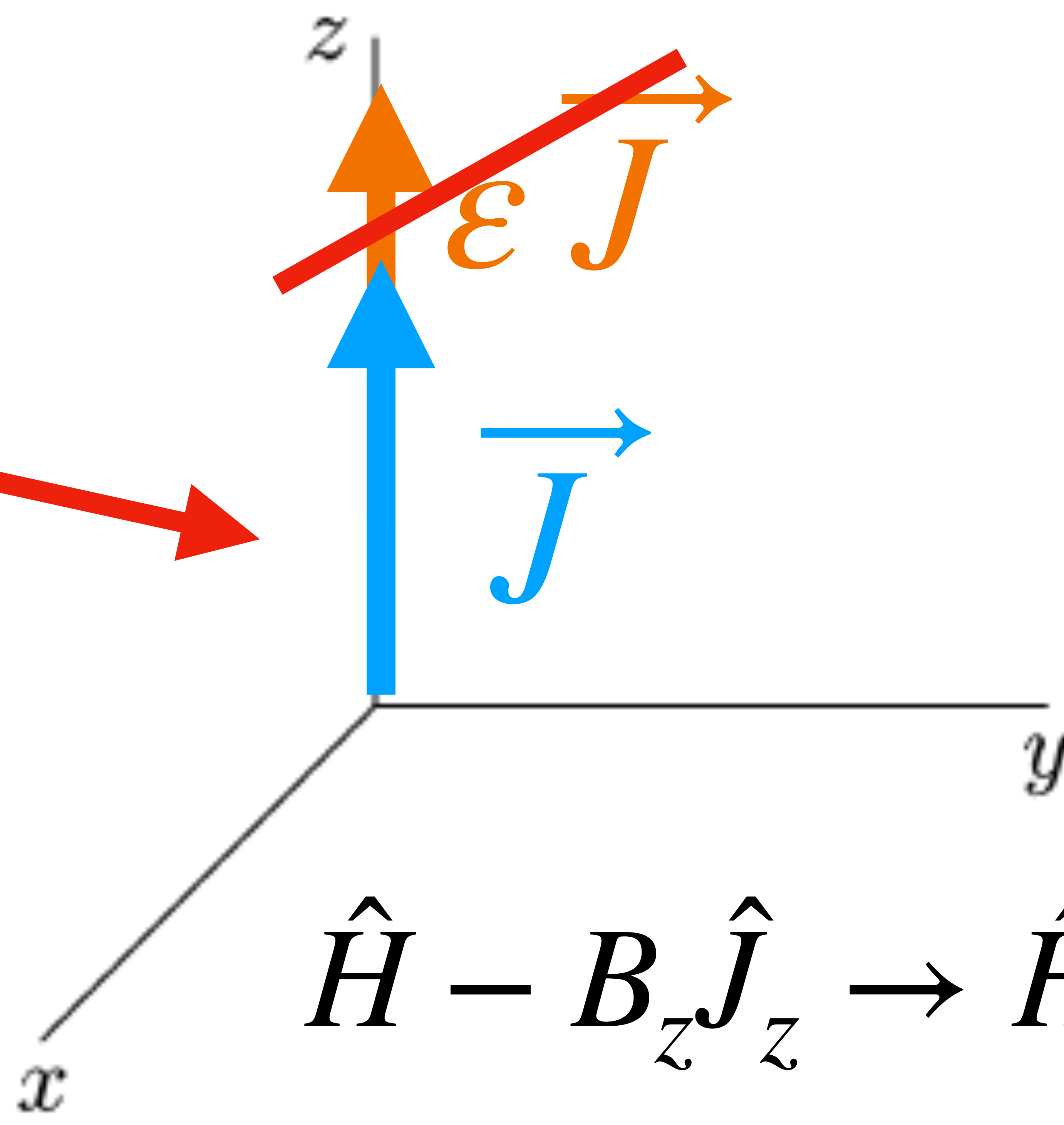
$$|\Psi_J\rangle = |\Psi_{J,J_z=J}\rangle + \varepsilon \sum_{J_B} C_{J_B} |\Psi_{J_B}\rangle$$

Projection of NQS



What is measured

$$\mu = \langle J, J_z = J | \mu_z | J, J_z = J \rangle$$

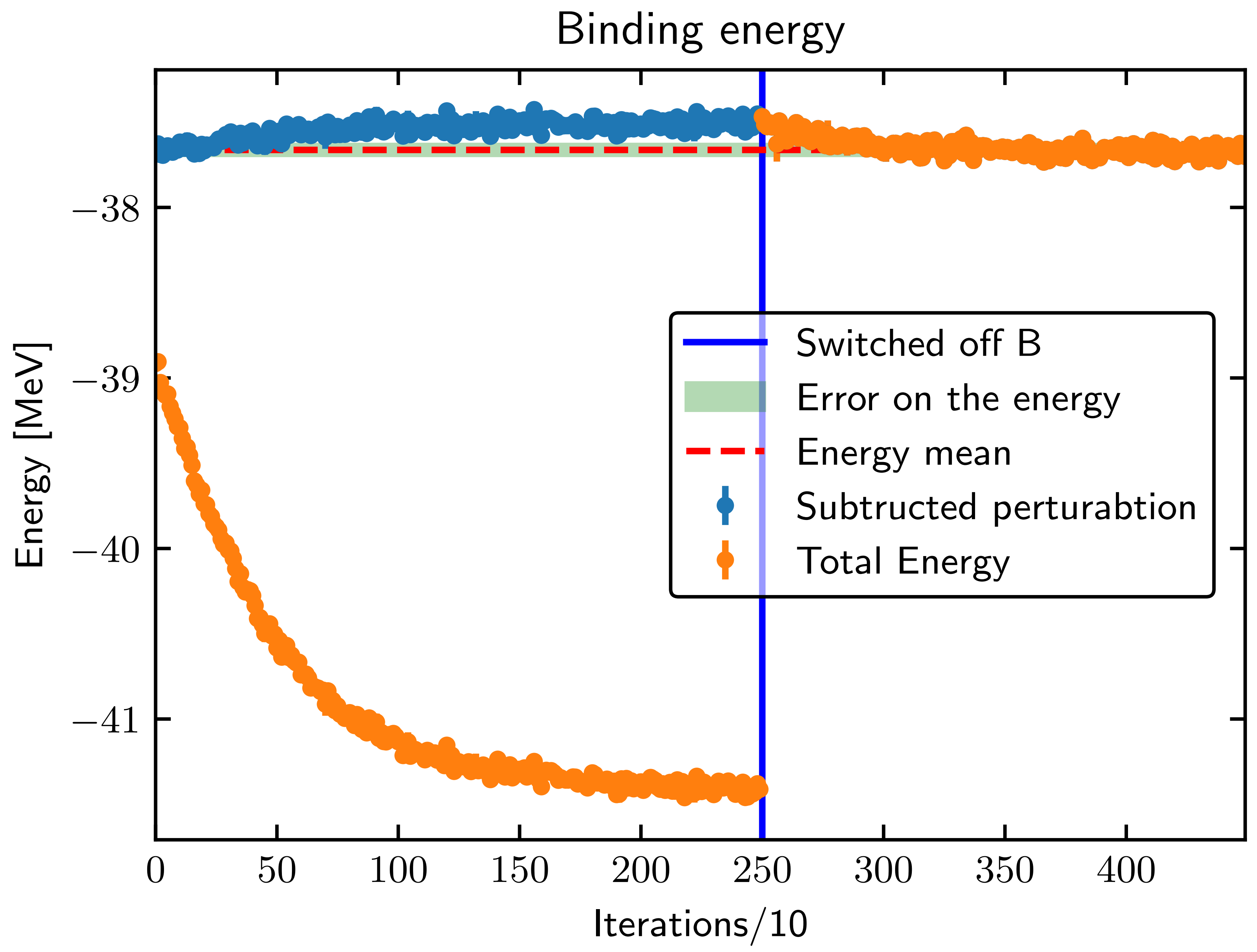


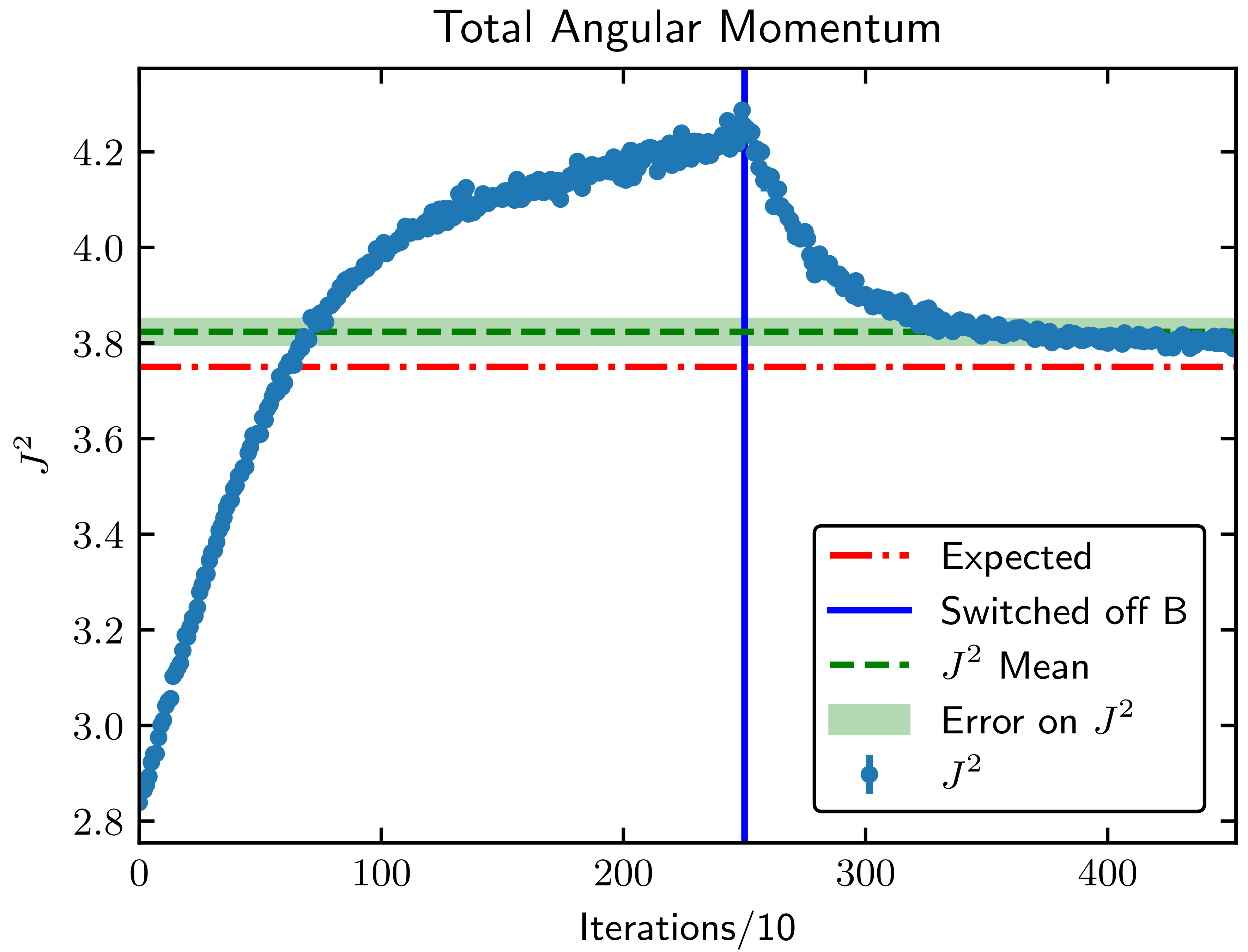
$$\hat{H} - B_z \hat{J}_z \to \hat{H}$$

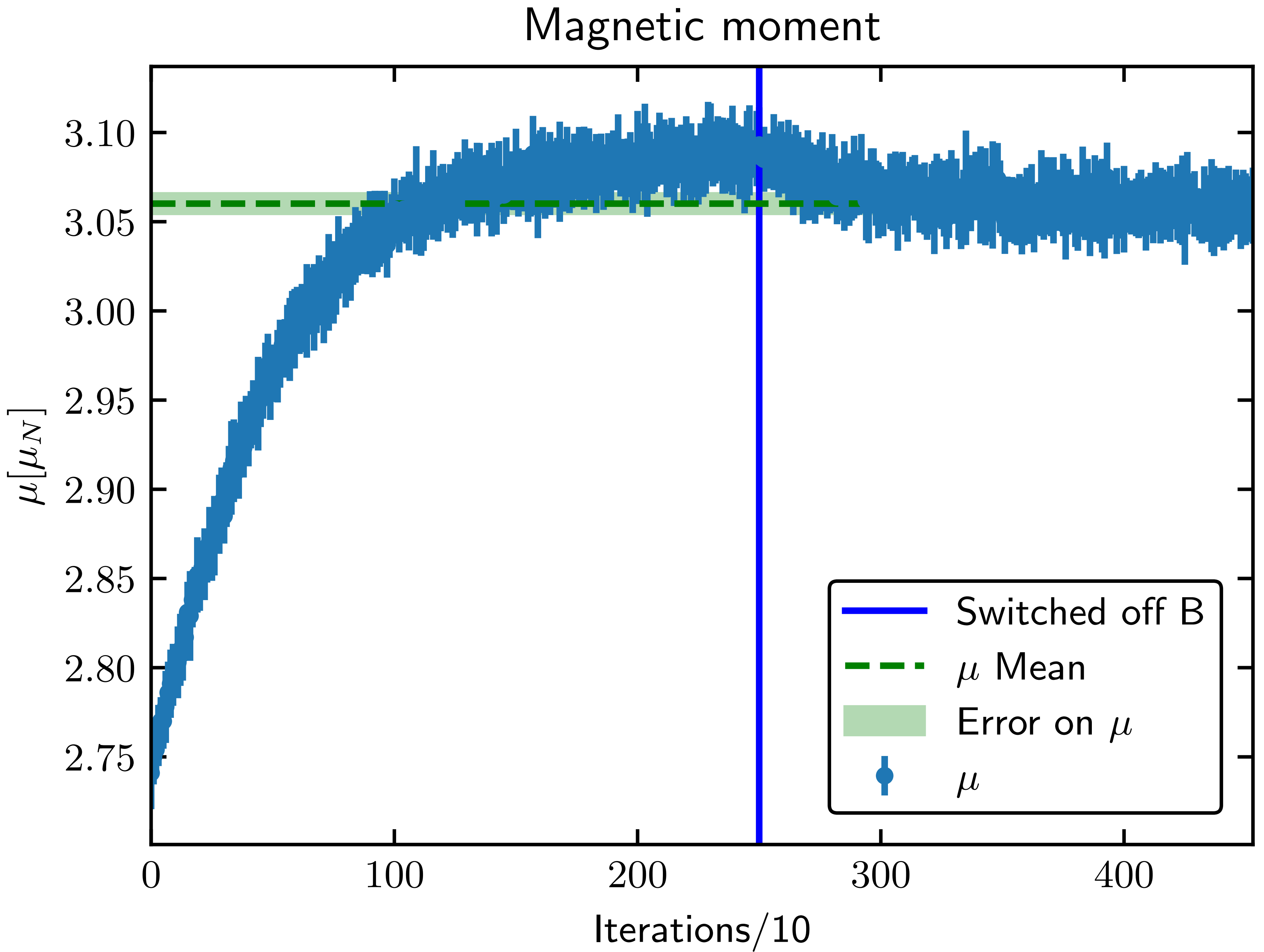
$$|\Psi_J\rangle = |\Psi_{J,J_z=J}\rangle + \varepsilon \sum_{J_B} C_{J_B} |\Psi_{J_B}\rangle$$

Projection on NQS

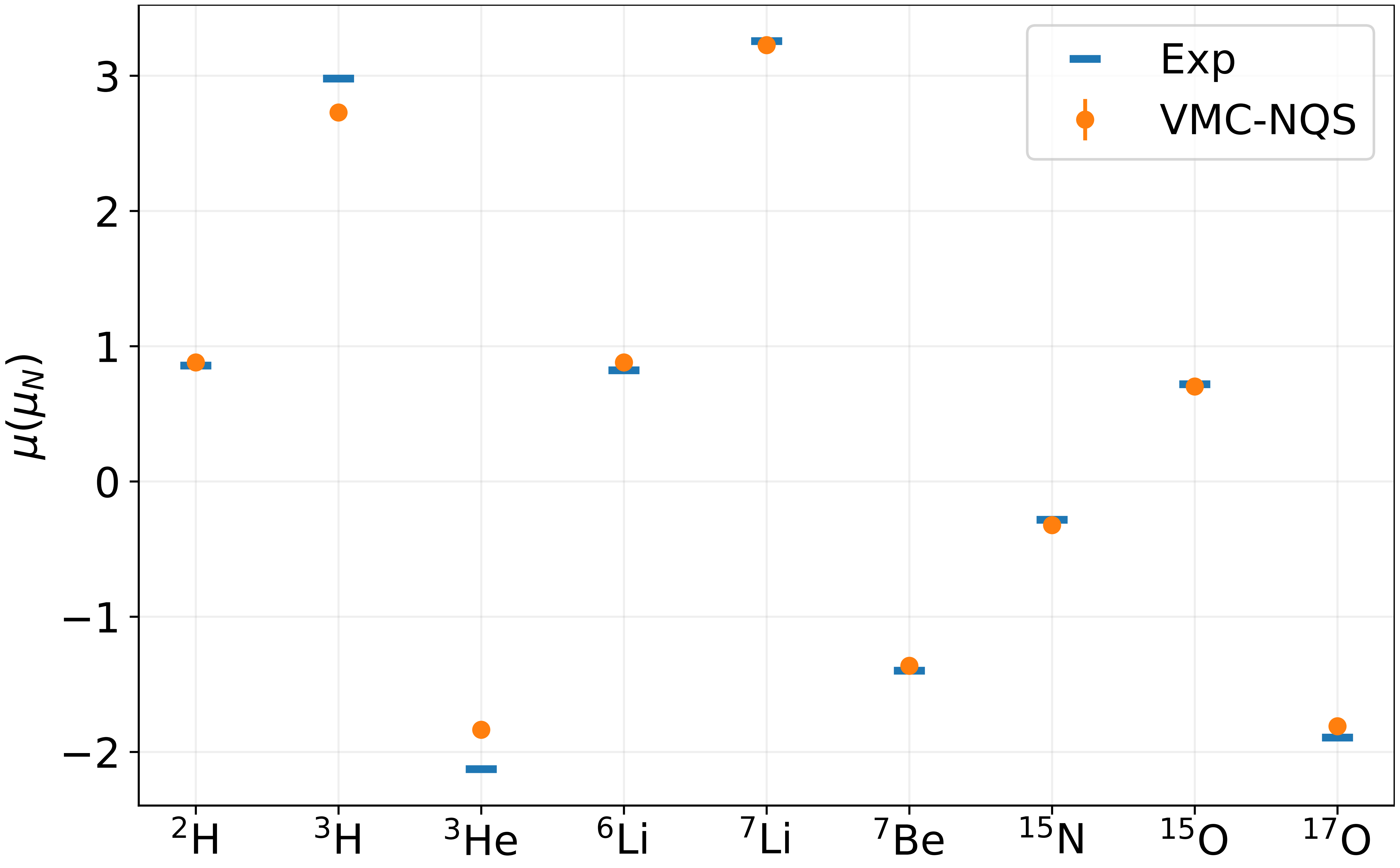
- The magnetic field B_z is a small perturbation
- Projection on the maximal $\hat{J}$ eigenstate (also on other using Wigner-Eckart)
- Extraction of the physical magnetic moment







Magnetic moments of selected light nuclei



- ^{3}H and ^{3}He require two-body currents
- Good agreement for the remaining:

  NQS reconstruct with the pionless EFT hamiltonian the shell-model structure without any ansatz

- More sophisticated interactions need two-body currents [see AFDMC and GFMC cresults]

Summary

Part I

- The isovector currents (OPE+CT @N3LO) seems to be crucial for reproducing the magnetic form factors
- Mechanism can be explained by np dominance in nuclei. Universality of the EM transitions (play a role for heavier nuclei)

Part II

- Pionless EFT can naturally generates the shell-model structure of light nuclei
- The magnetic moments are the test probe for this
- We still need two-body currents for exactly reproducing magnetic moments

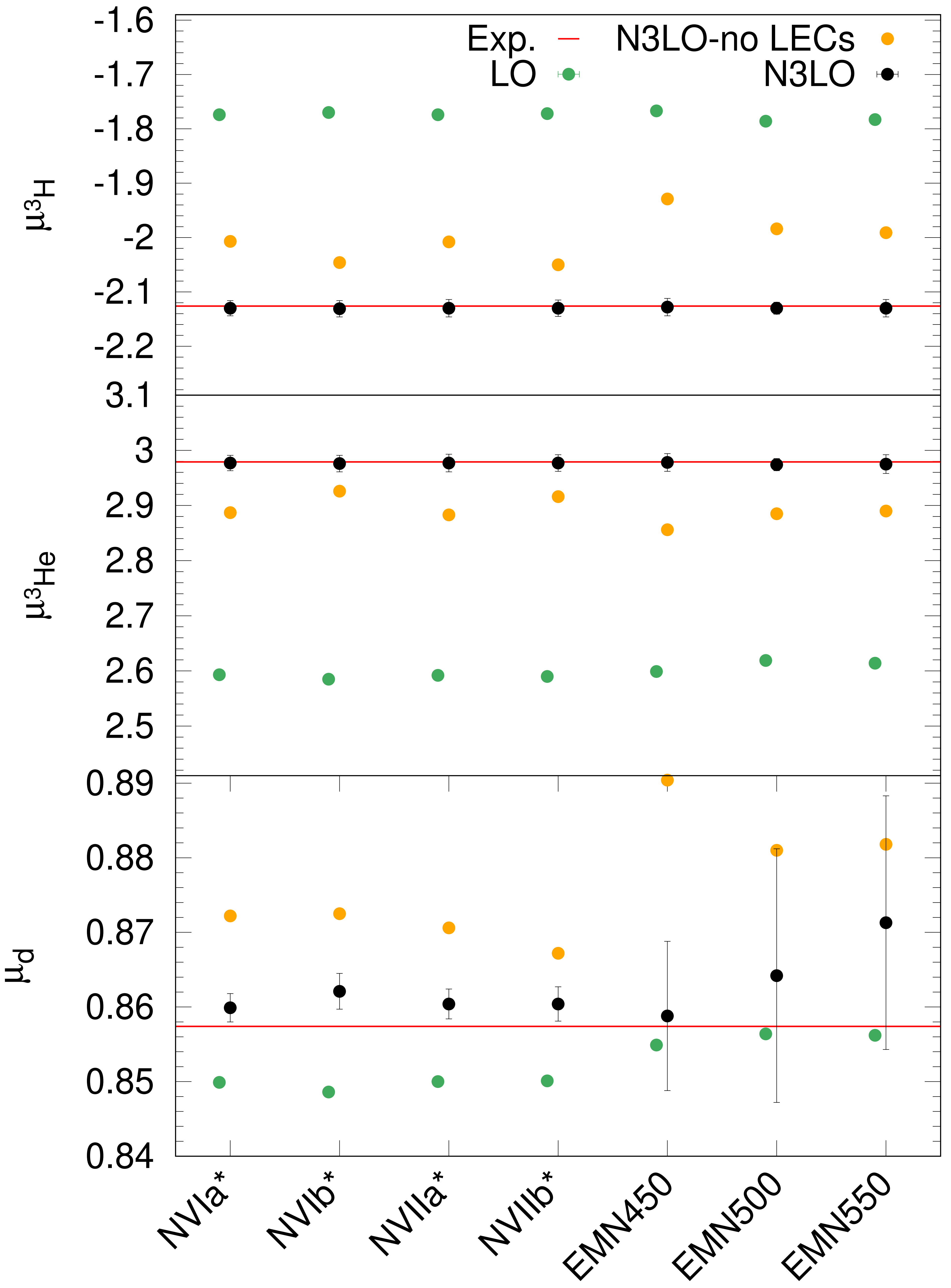
NERSC National Energy Research Scientific Computing Center

Sparse

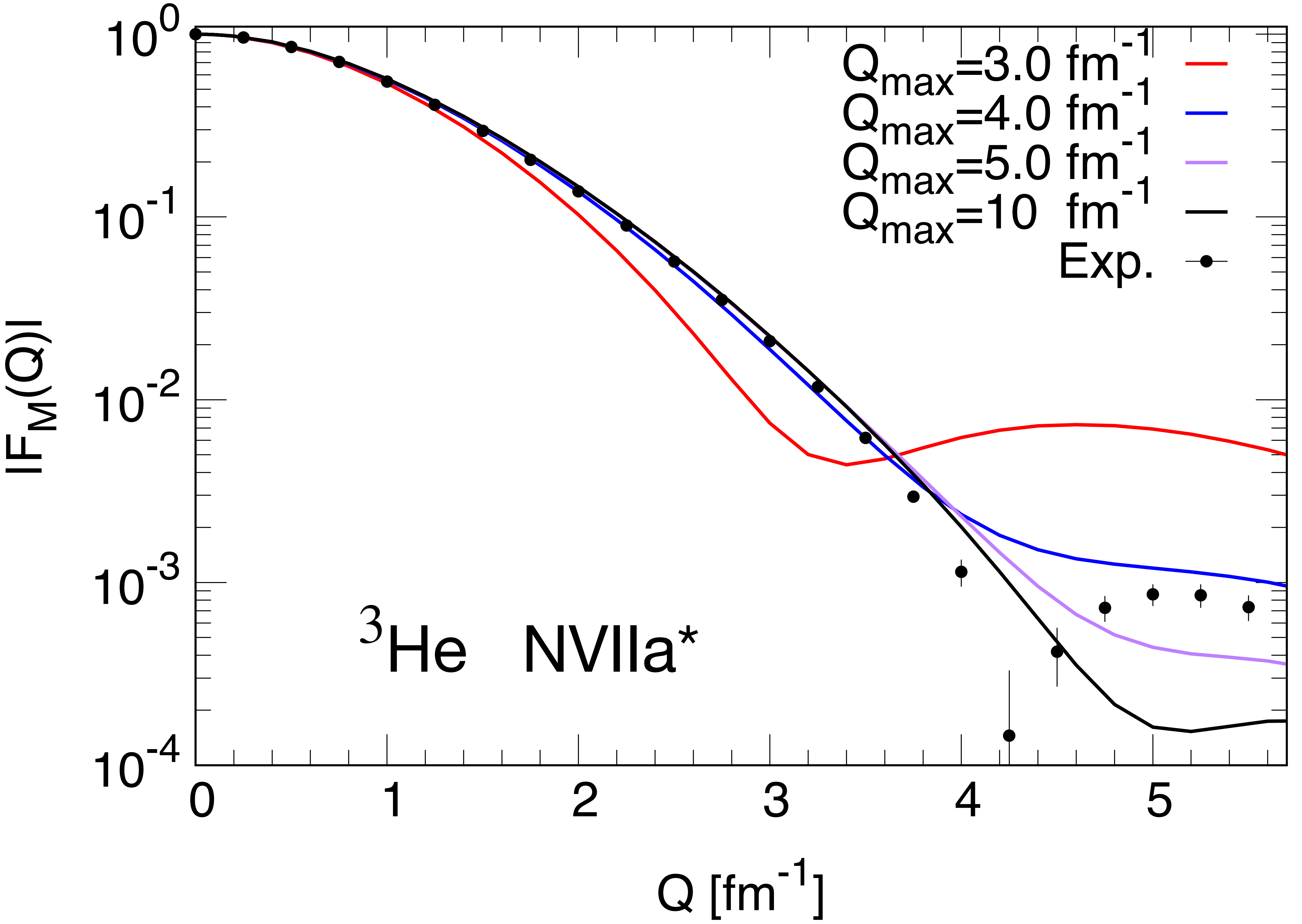
Results of the fit

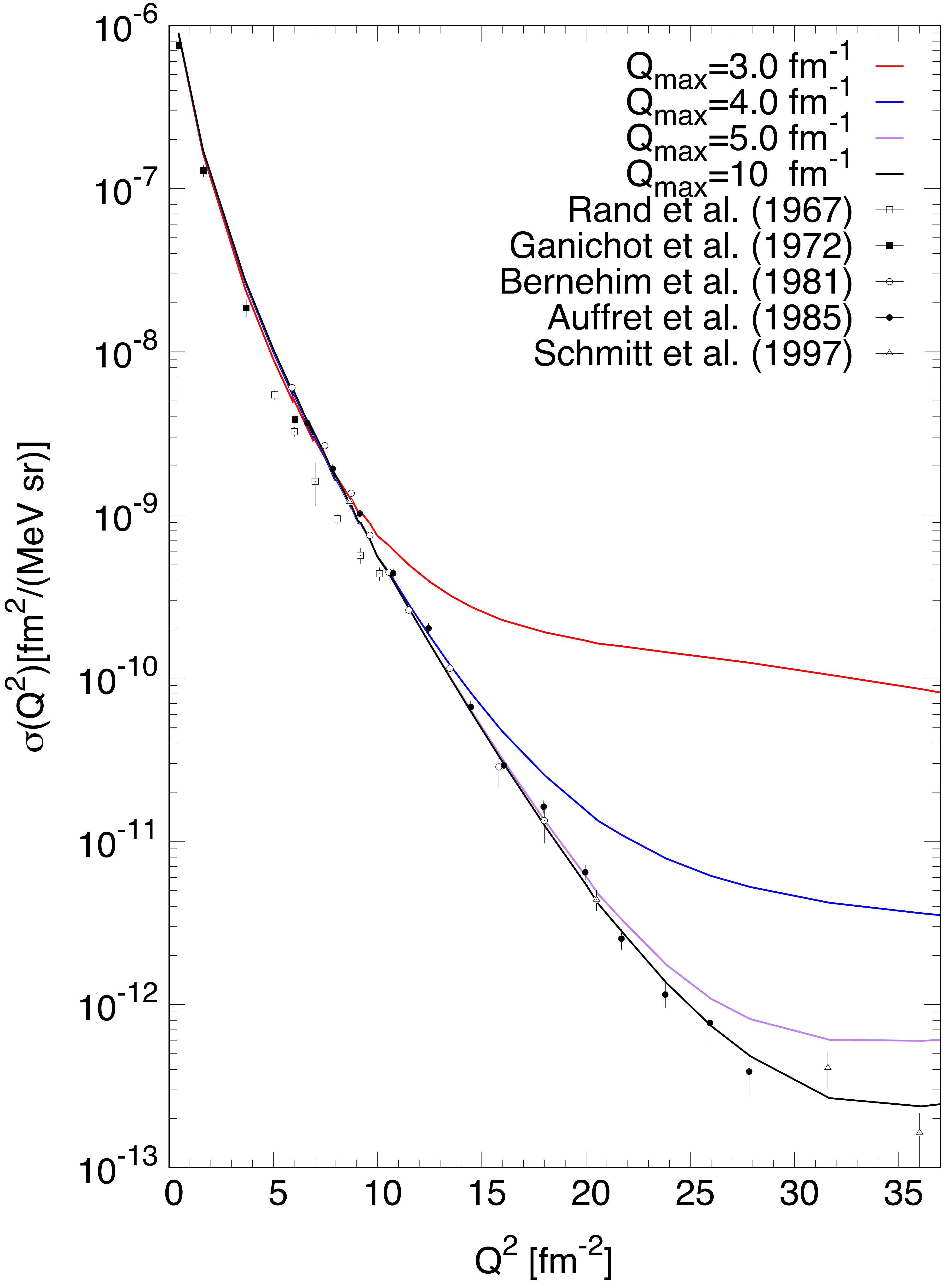
Pot.	χ^2/ndf	χ^2/ndf (no Rand)
NVIa*	9.9	2.0
NVIb*	10.2	2.3
NVIIa*	11.6	2.5
NVIIb*	11.6	2.6
EMN450	11.3	2.8
EMN500	14.7	4.7
EMN550	17.7	7.9

- ndf~40
- Removing Rand *et al.* data, χ^2 improves

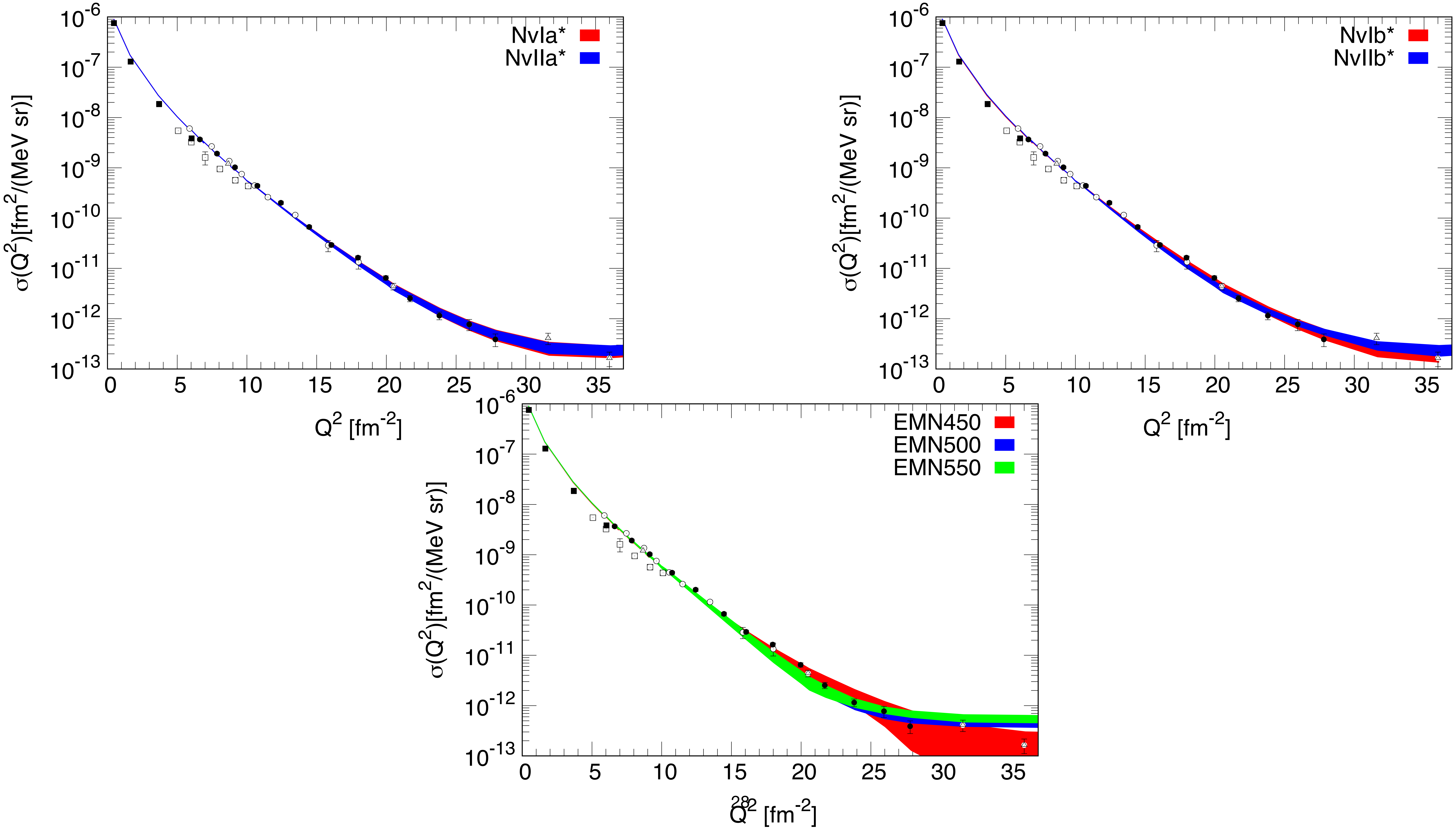


Dependence on Q^2_{max}

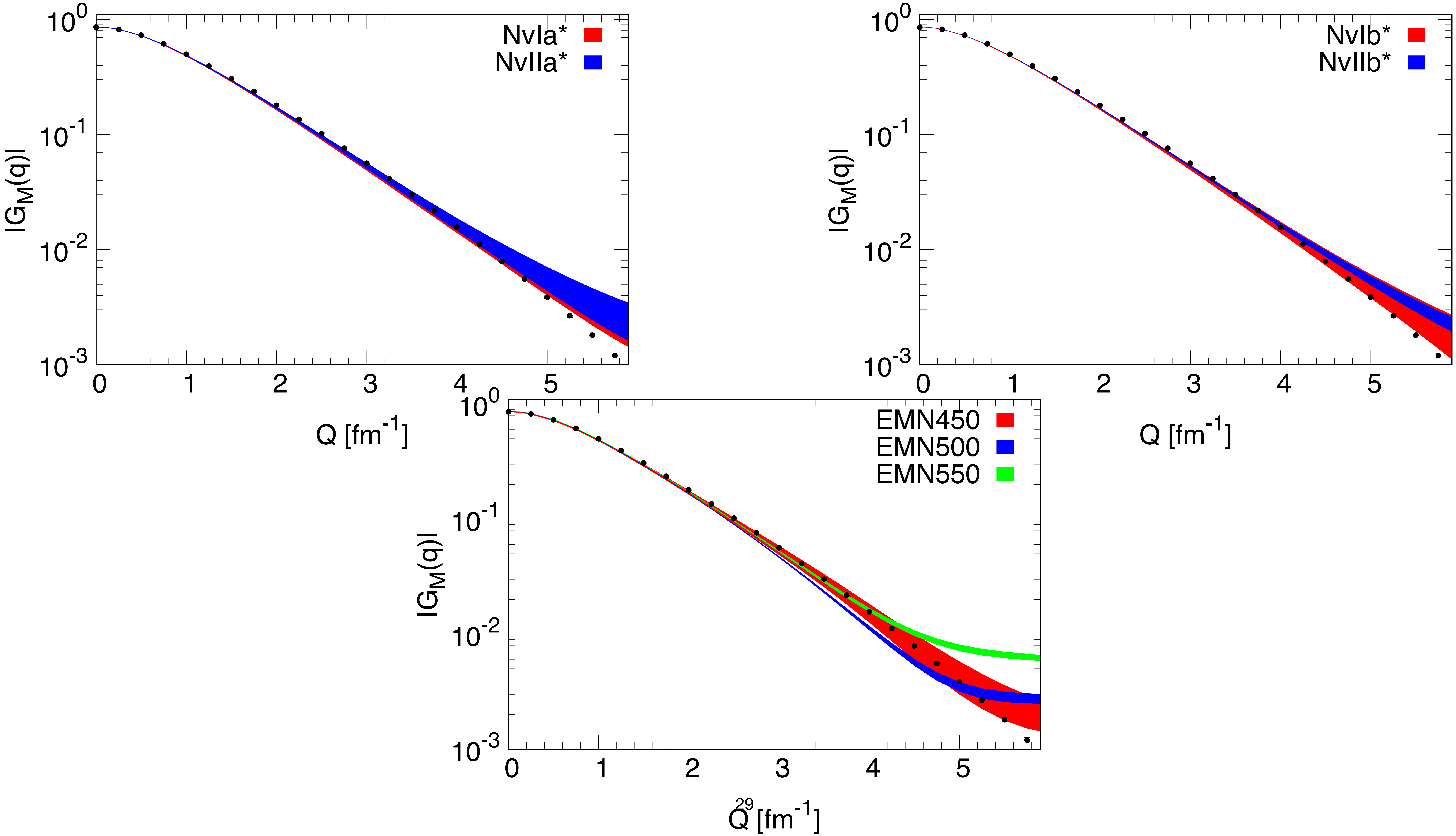




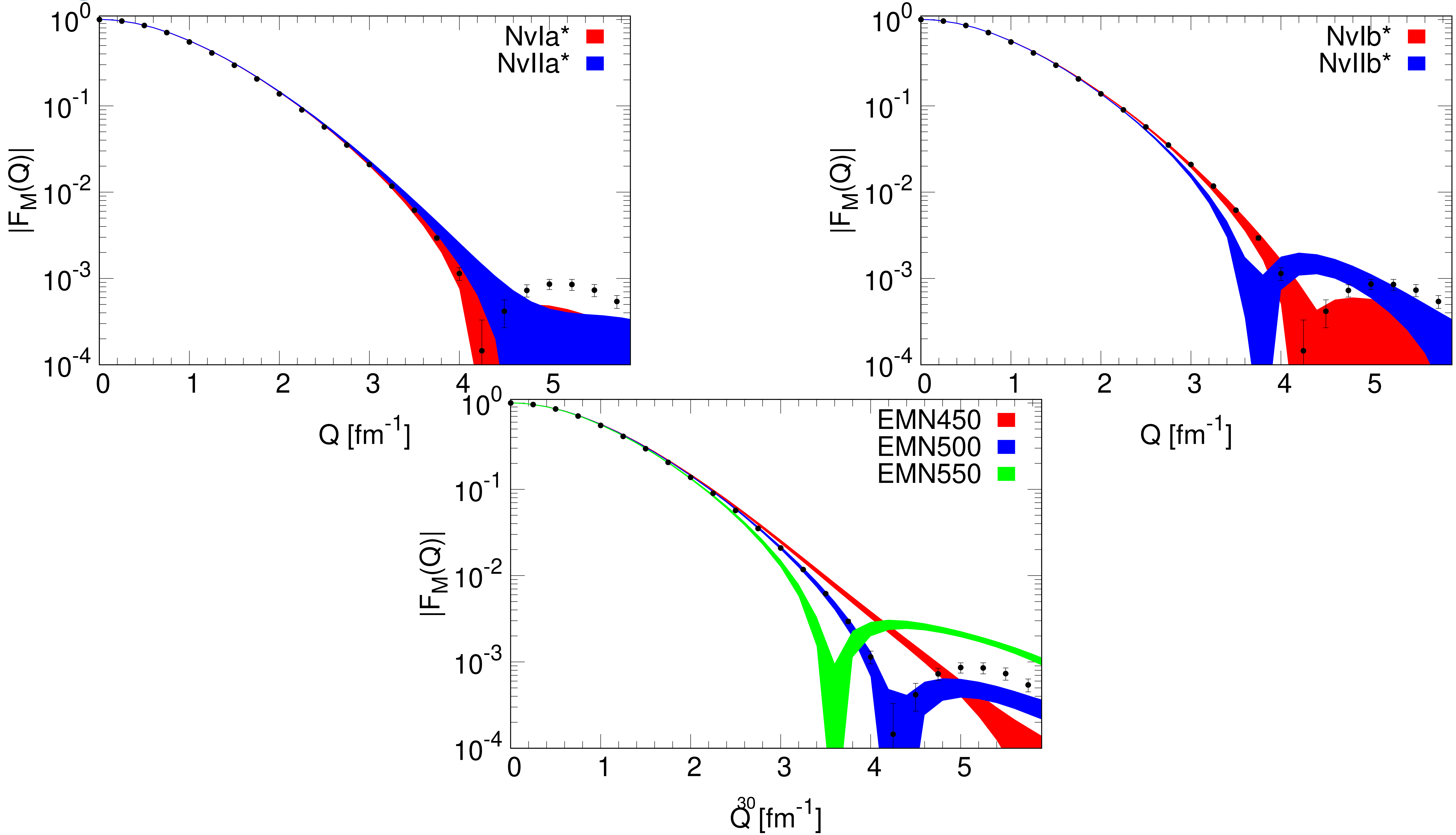
d-threshold


NvIa*
NvIIa*
NvIb*
NvIIb*
EMN450
EMN500
EMN550
σ(Q²)[fm²/(MeV sr)]
Q² [fm⁻²]

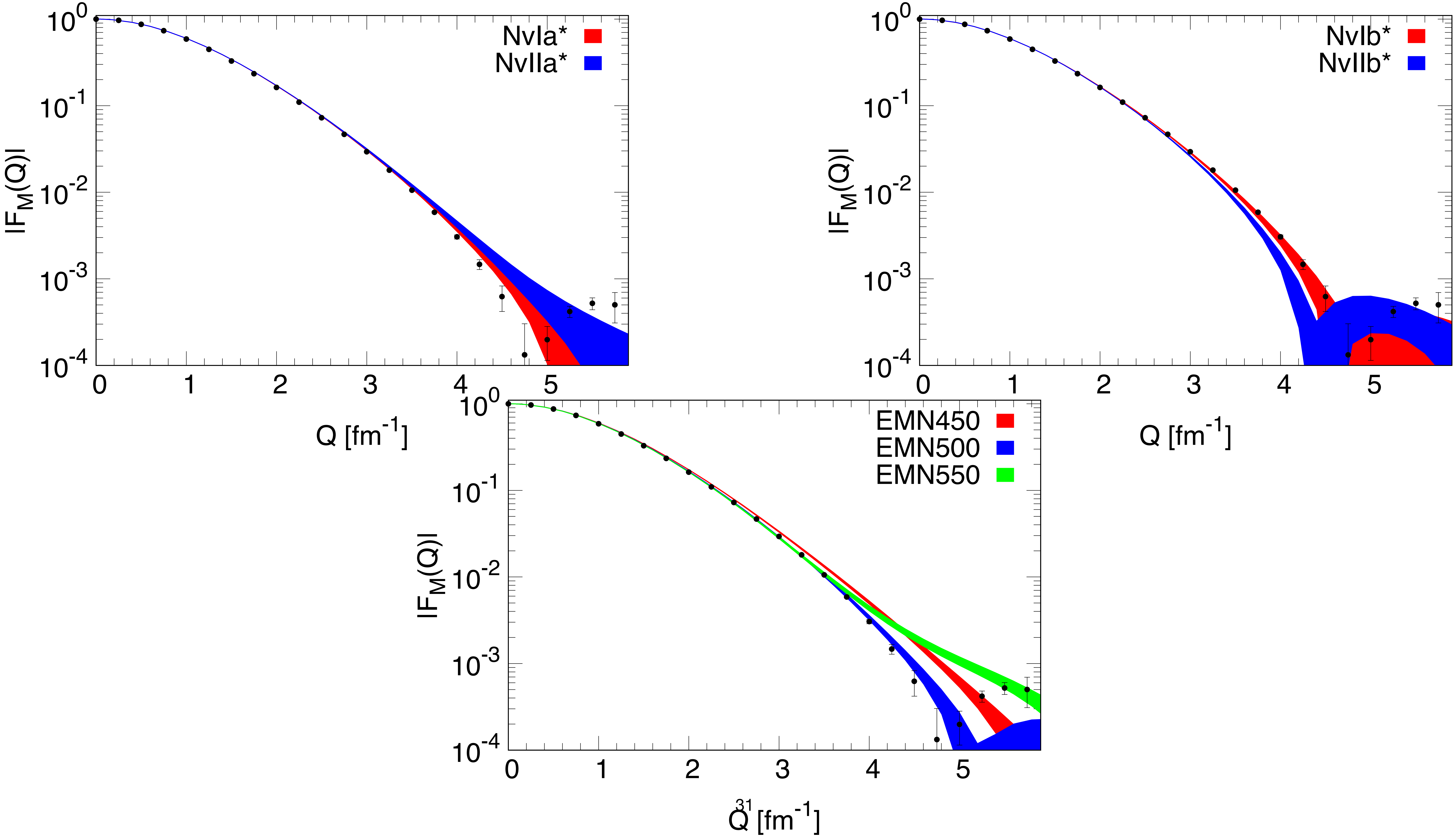
Magnetic form factors of ^{2}H



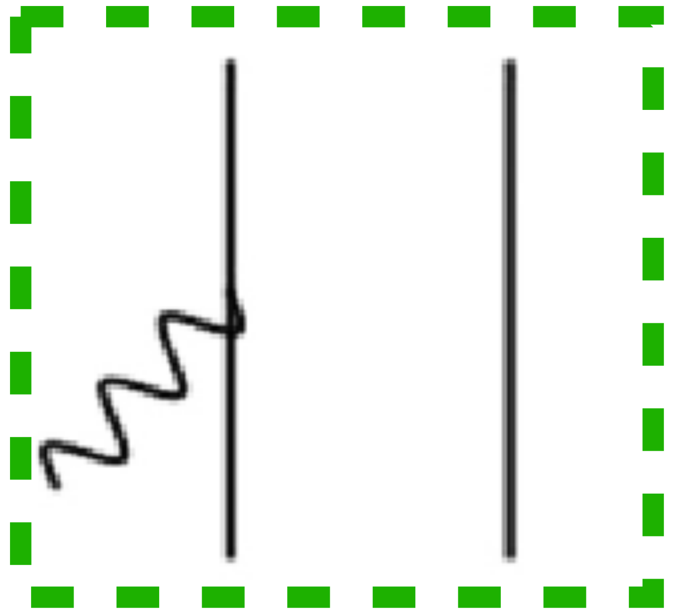
Magnetic form factors of ^{3}He

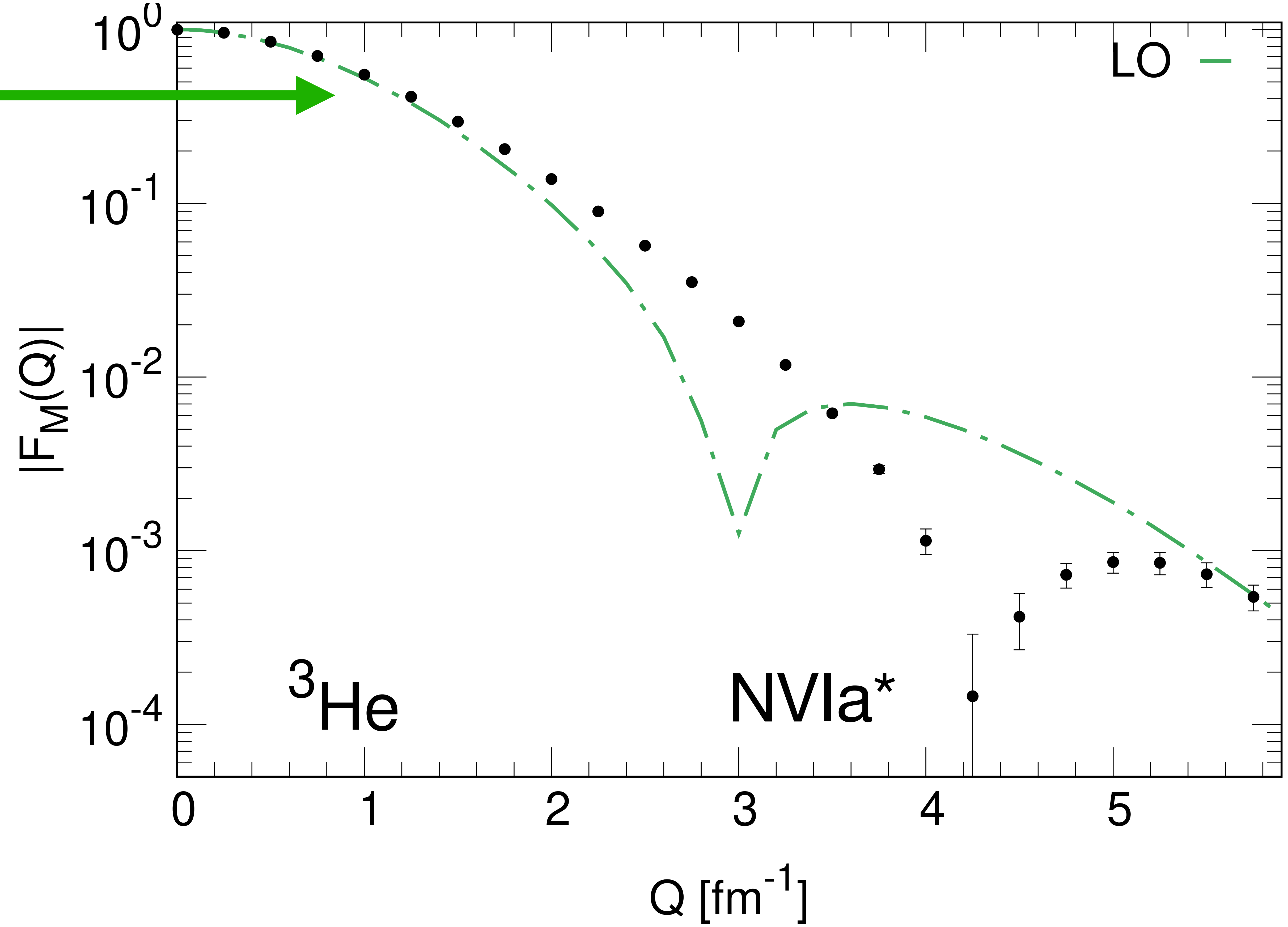


Magnetic form factors of ^{3}H

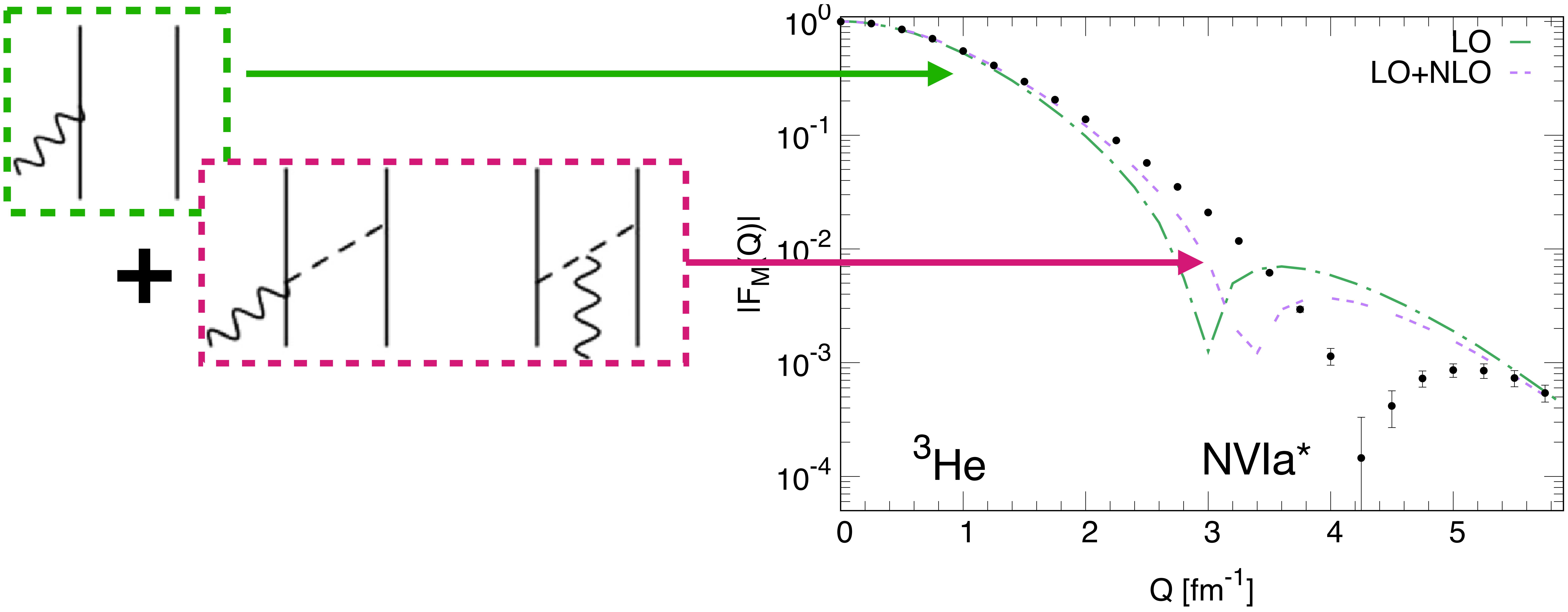


Prediction of A=3 Magnetic Form Factors

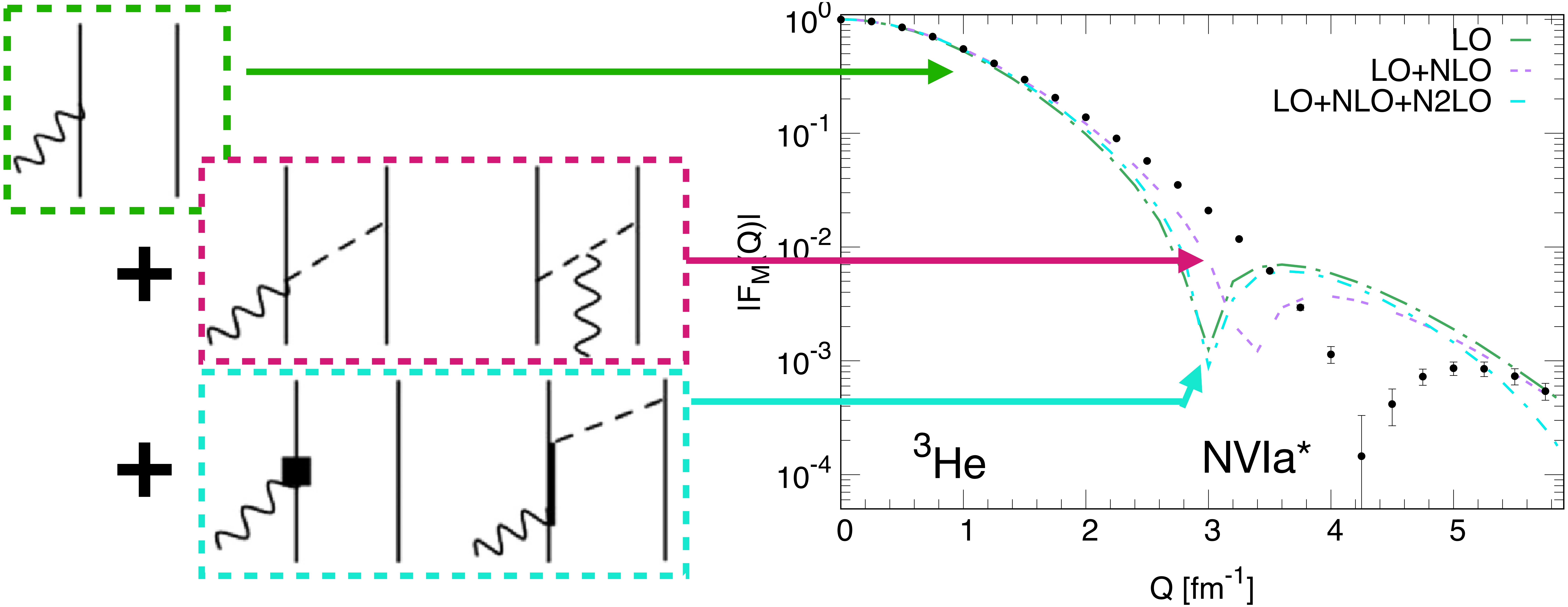




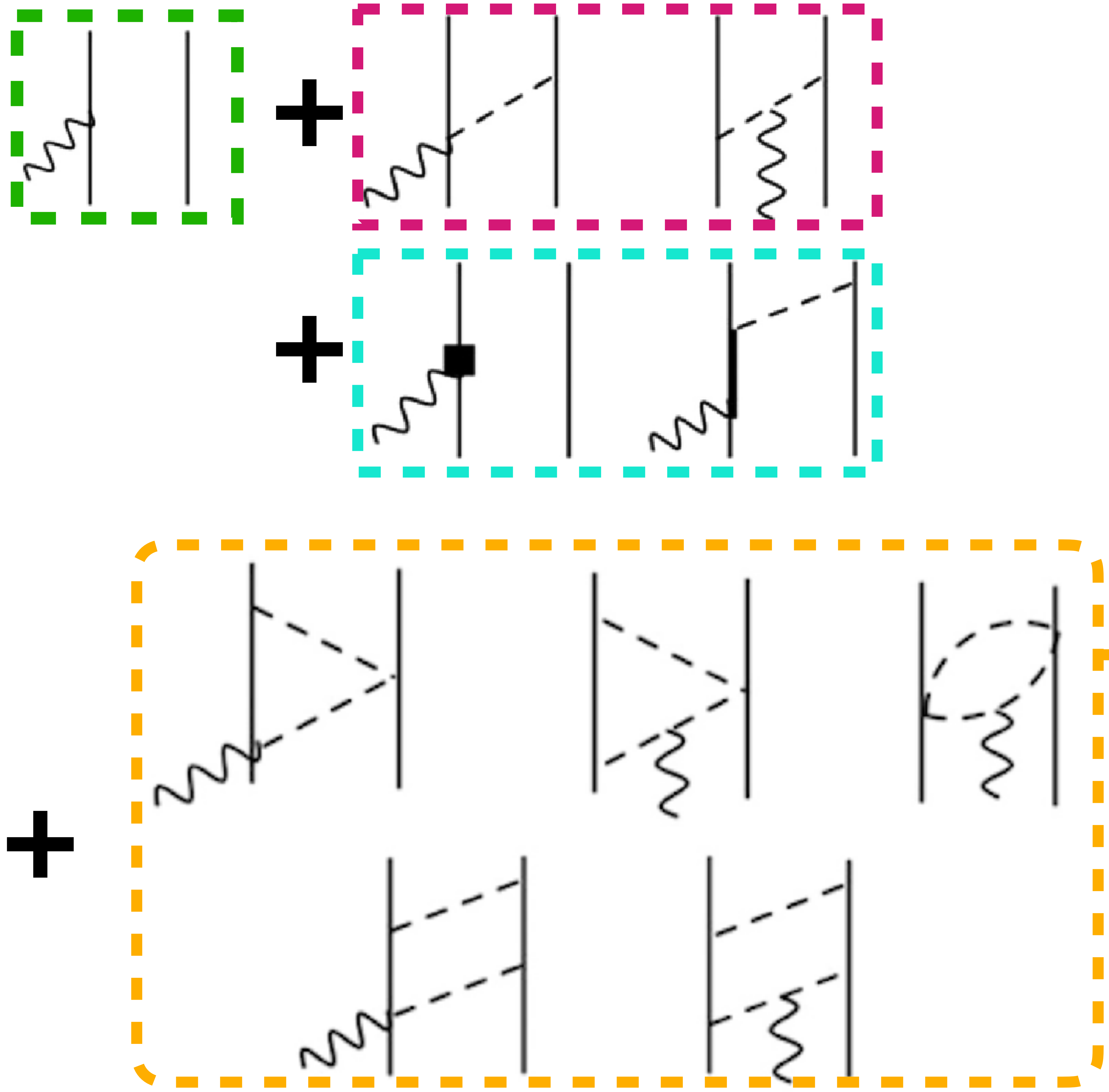
Prediction of A=3 Magnetic Form Factor

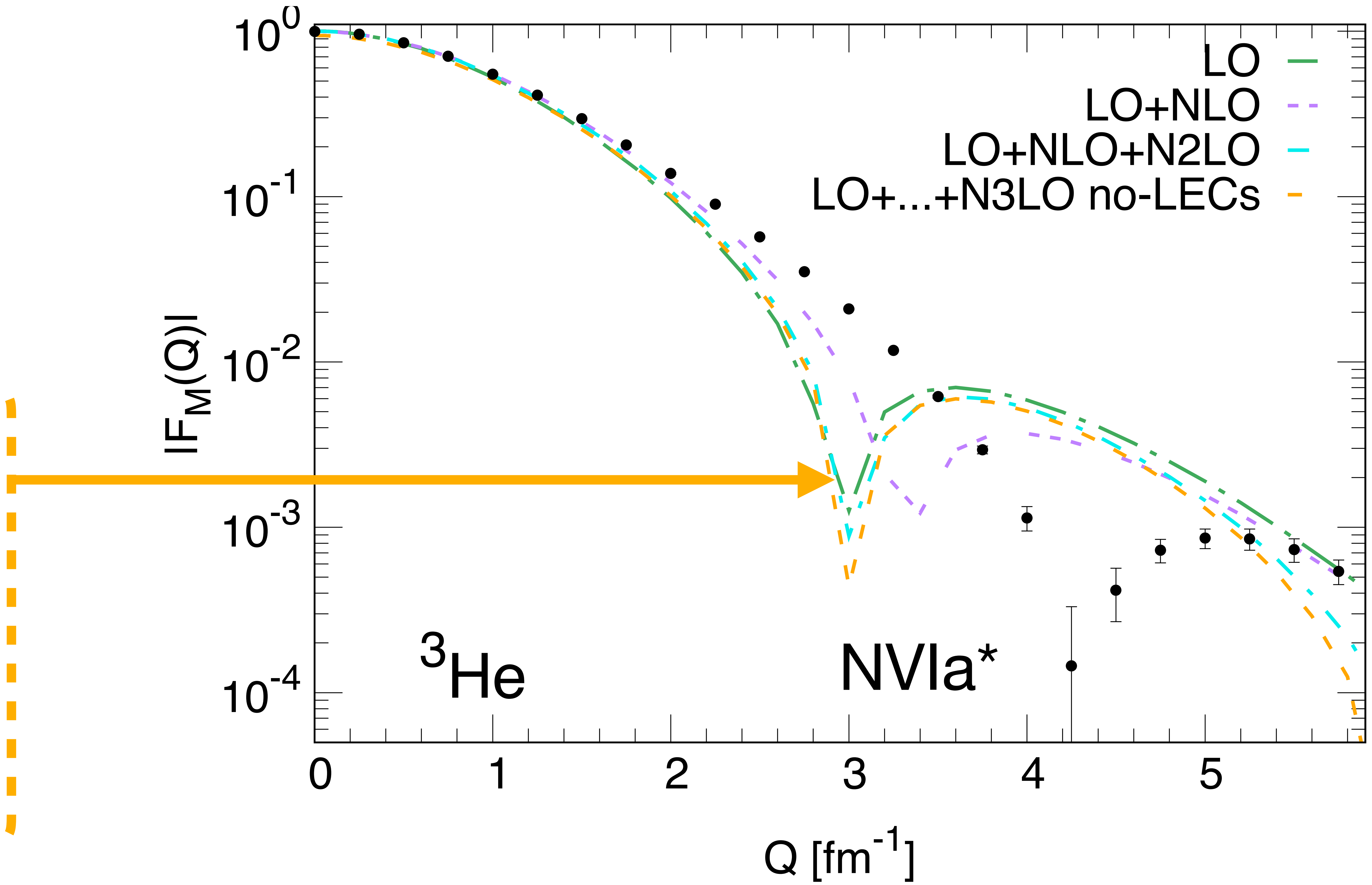


Prediction of A=3 Magnetic Form Factor

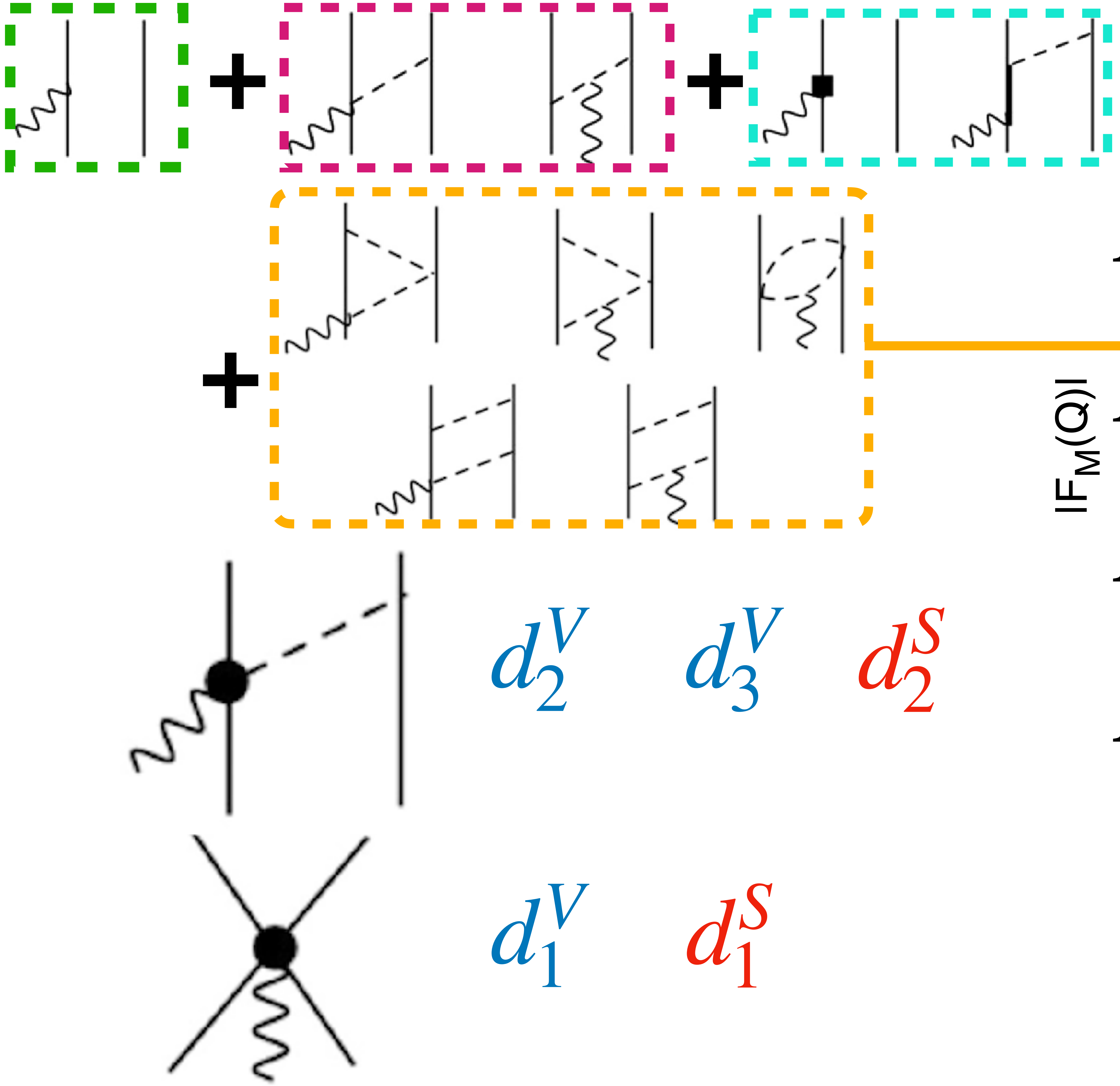


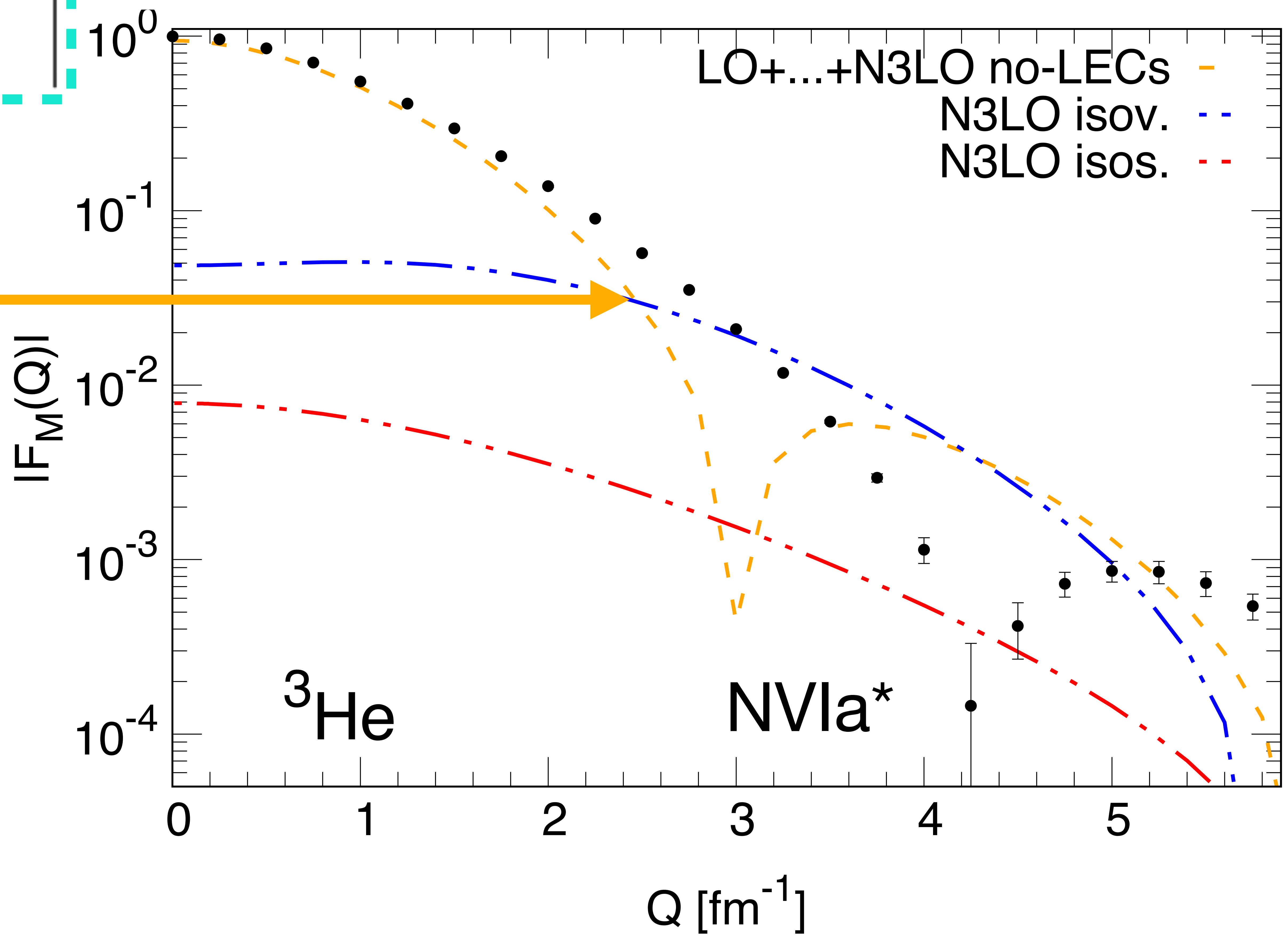
Prediction of A=3 Magnetic Form Factor





Prediction of A=3 Magnetic Form Factor



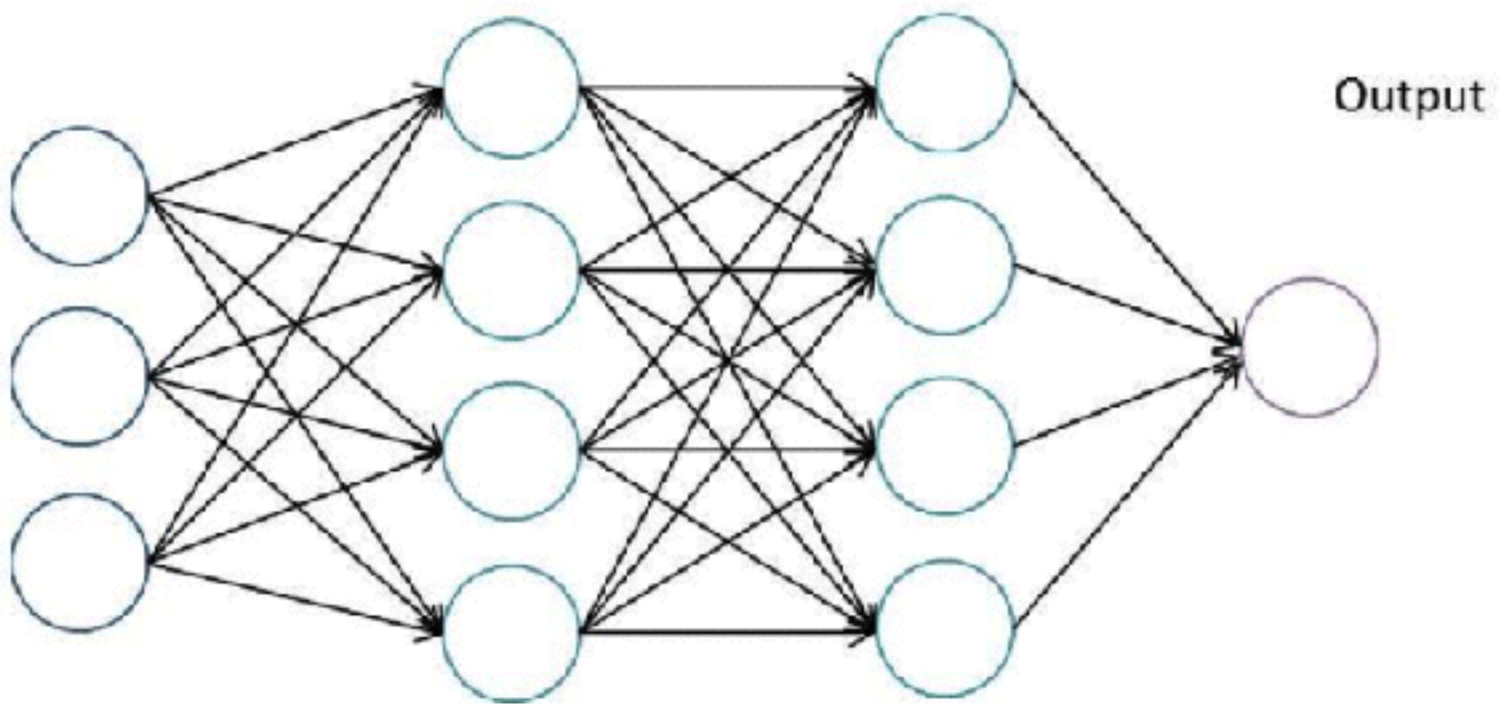


The NQS wave function

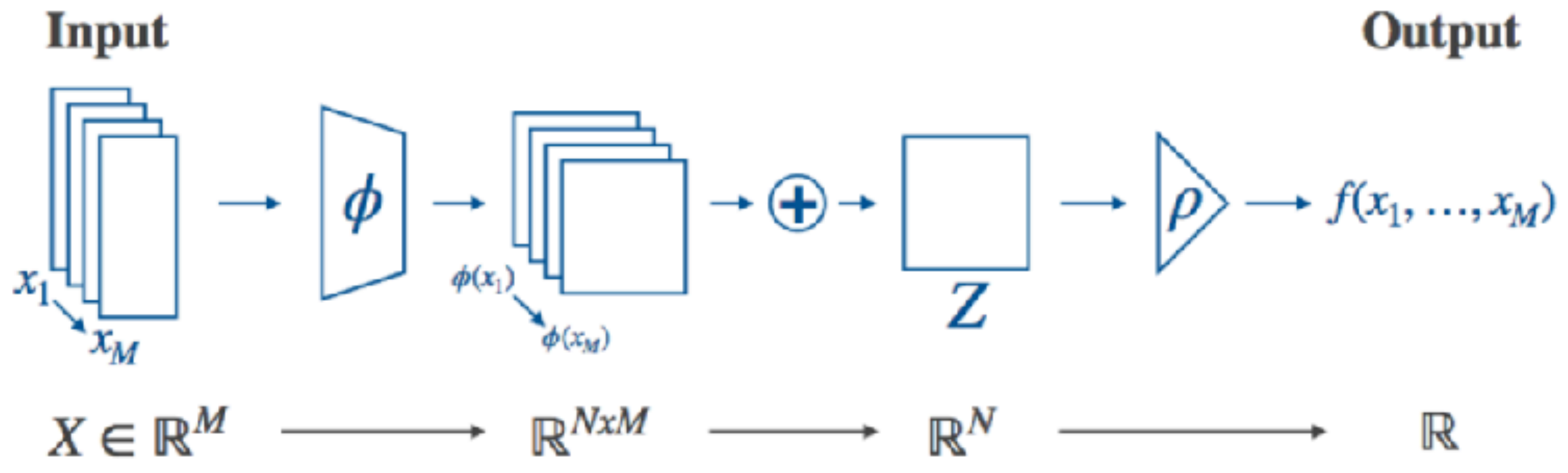
$$\Psi(X, W) \equiv \det \begin{bmatrix} \phi_v(X) & \phi_v(X_h) \\ \phi_h(X) & \phi_h(X_h) \end{bmatrix}$$

Antisymmetry

Fully connected neural networks



Deep sets neural networks



Enforce permutation invariance

The NQS wave function

$$\Psi(X, W) \equiv \det \begin{bmatrix} \phi_v(X) & \phi_v(X_h) \\ \phi_h(X) & \phi_h(X_h) \end{bmatrix}$$

- Antisymmetry
- Fully connected neural networks
- Deep sets neural networks

New features:

- Completely imaginary
- Message passing neural-network

Some references for the wave function:
C. Adams et al., Phys. Rev. Lett. 127, 022502 (2021)
A. Lovato et al., Phys. Rev. Res. 4, 043178 (2022)
J. Kim et al., arXiv:2305.08831 (2023)