Electromagnetic structure of light nuclei up to Q^2~1 GeV^2

Hall A/C Summer Collaboration Meeting

JLab, Newport News (VA), July 15, 2024

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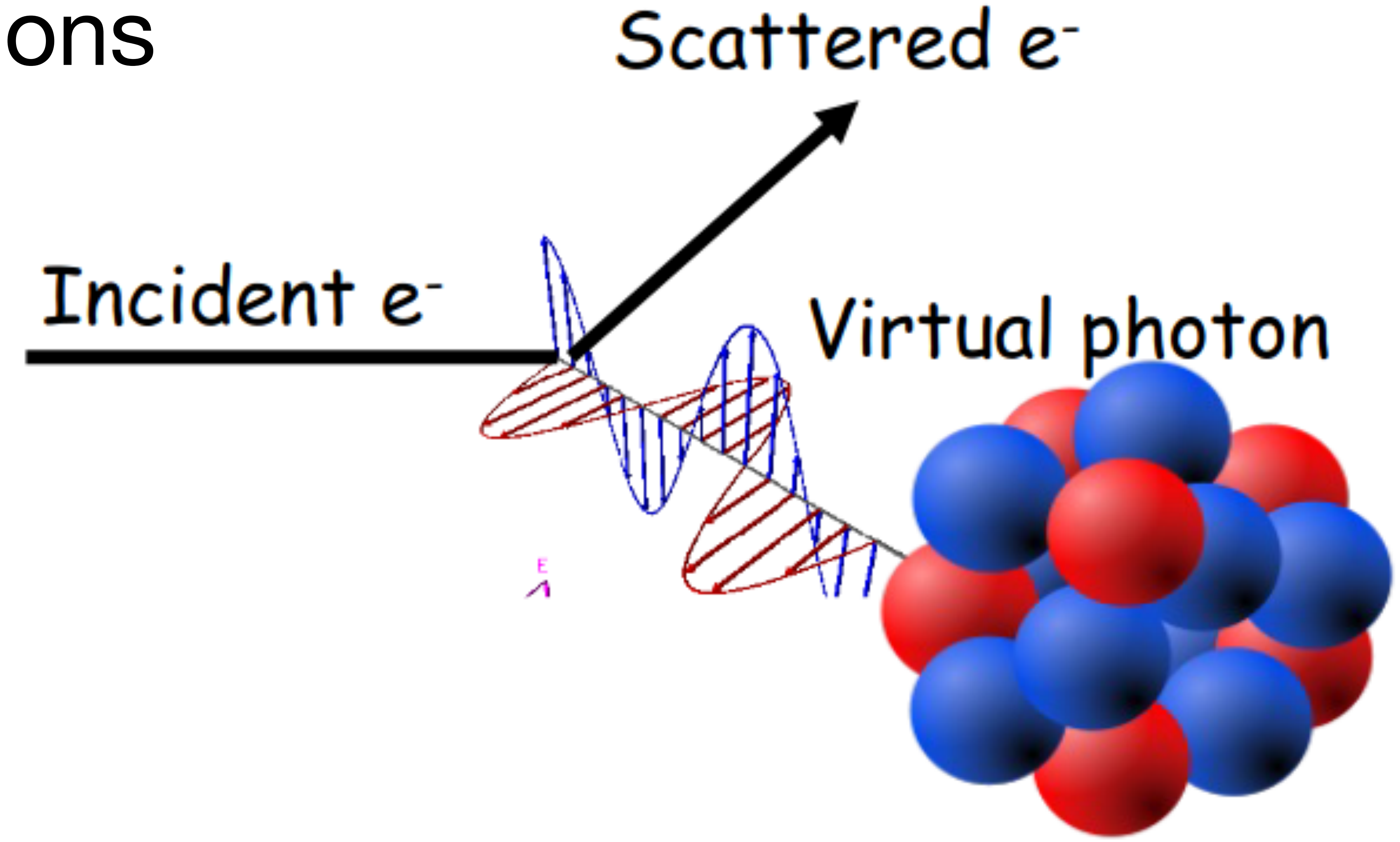
Experimental motivation

A low-energy prospective

Short Range Correlations
(CaFe exp.,…)

SIDIS in nuclei
(E12-06-014,…)

EMC effects
(MARATHON,…)



Exclusive pion
production

Neutrino physics
(see L. Andreoli talk)

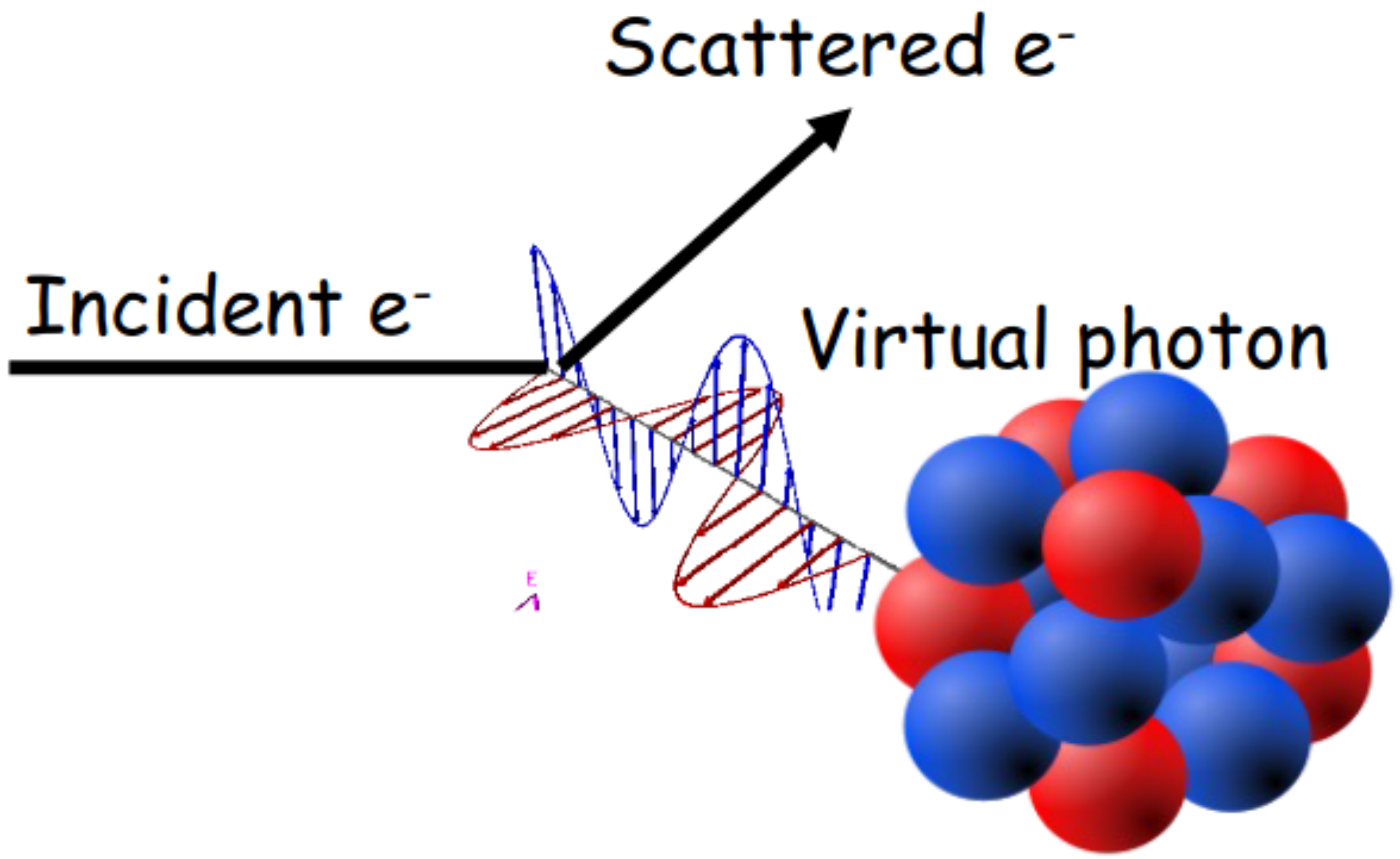
Hypernuclei

Understanding and describing the nuclear correlations is crucial to disentangle the physics Hall A/C are looking for

Motivation of this talk

The goal of the project

- Obtain nuclear currents reliable in a region of momentum transfer $Q^2 \sim 0 - 3$ GeV²
- Perform calculation considering the full nuclear dynamics
- Introducing explicit emission of mesons (pions,…)
- Integrating the result with "medium" energy nuclear physics models (non perturbative region)



In this talk:

test of the EM Currents on electrons elastic scattering

Magnetic form factors (MFF) using χEFT*

References

- Fit of the currents and test on few-body nuclei

[A.G. and R. Schiavilla, Phys. Rev. C 106, 044001 (2020)]

- Prediction of magnetic form factors of heavier systems

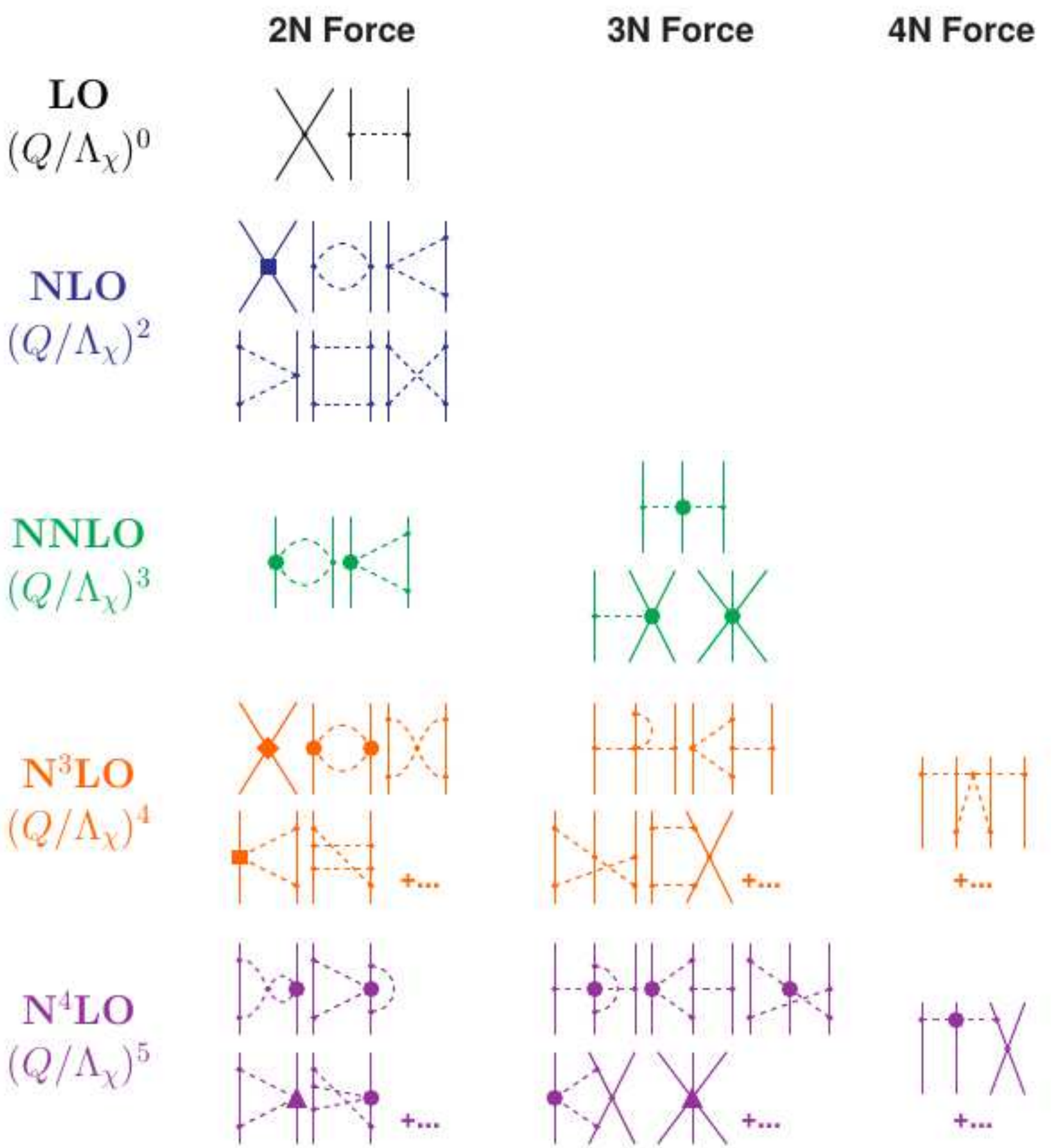
[G. Chambers-Wall, A. G., G. B. King, S. Pastore, M. Piarulli, R. Schiavilla, R. B. Wiringa, arXiv:2407.04744, arXiv:2407.03487]

Chiral effective field theory

- Only Nucleons and Pions as degrees of freedom $(M_{QCD} \sim 1$ GeV)
- Direct connection with QCD: chiral symmetry (+ discrete symmetries + Lorentz invariance)
- Low Energy Constants (LECs): fitted on experimental data
- Organize the interaction as a power expansion Q/M_{QCD} (controlled errors)

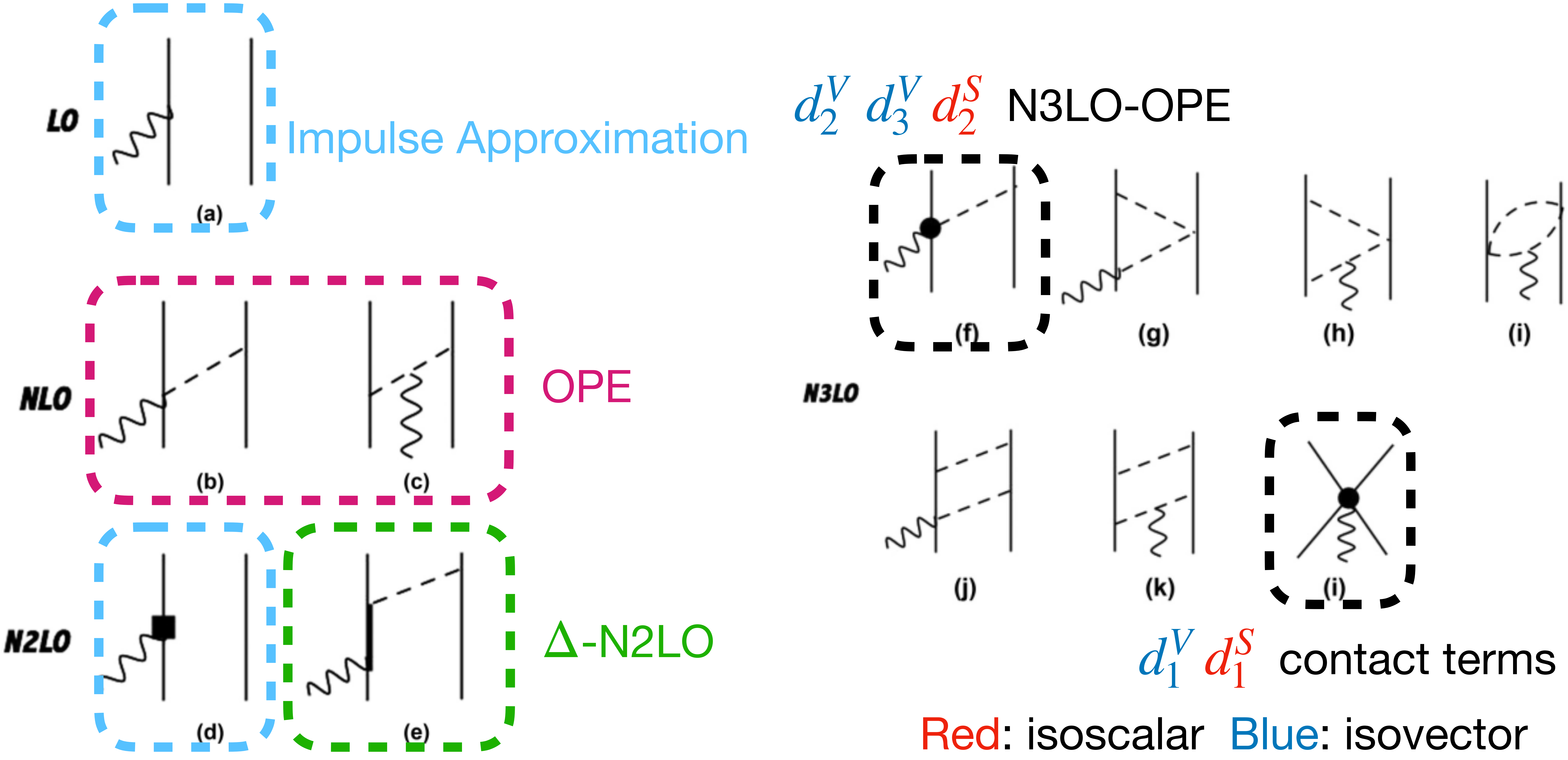
"Semi-phenomenological"

χEFT approach to extend theory to higher momenta



Phys. Rev. C **96**, 024004 (2017)
Phys. Rev. Lett. **115**, 122301 (2015)

The chiral currents

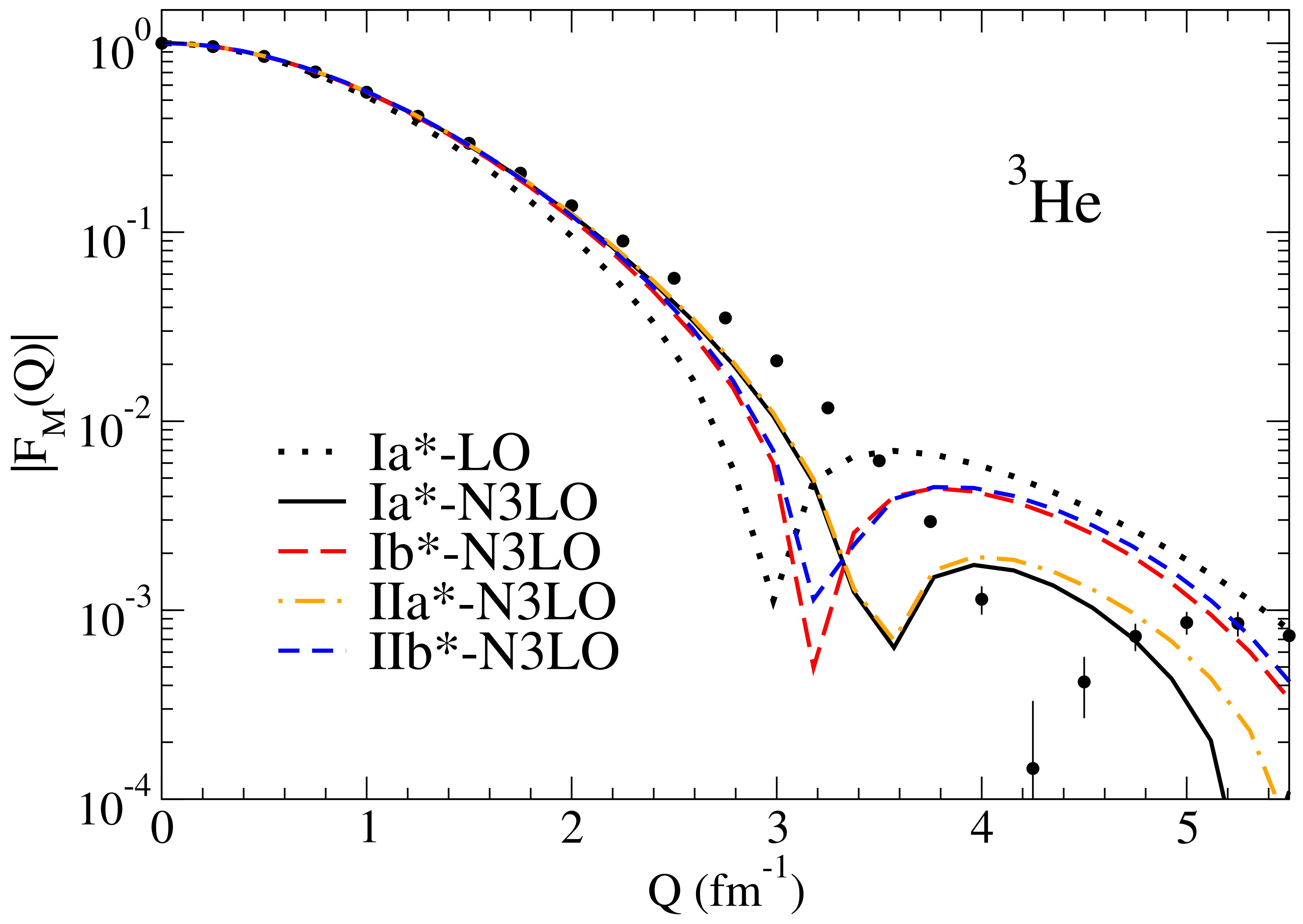


Currents from [PRC 80, 034004 (2009)] and [PRC 99, 034005 (2019)]

How to fix the LECs I

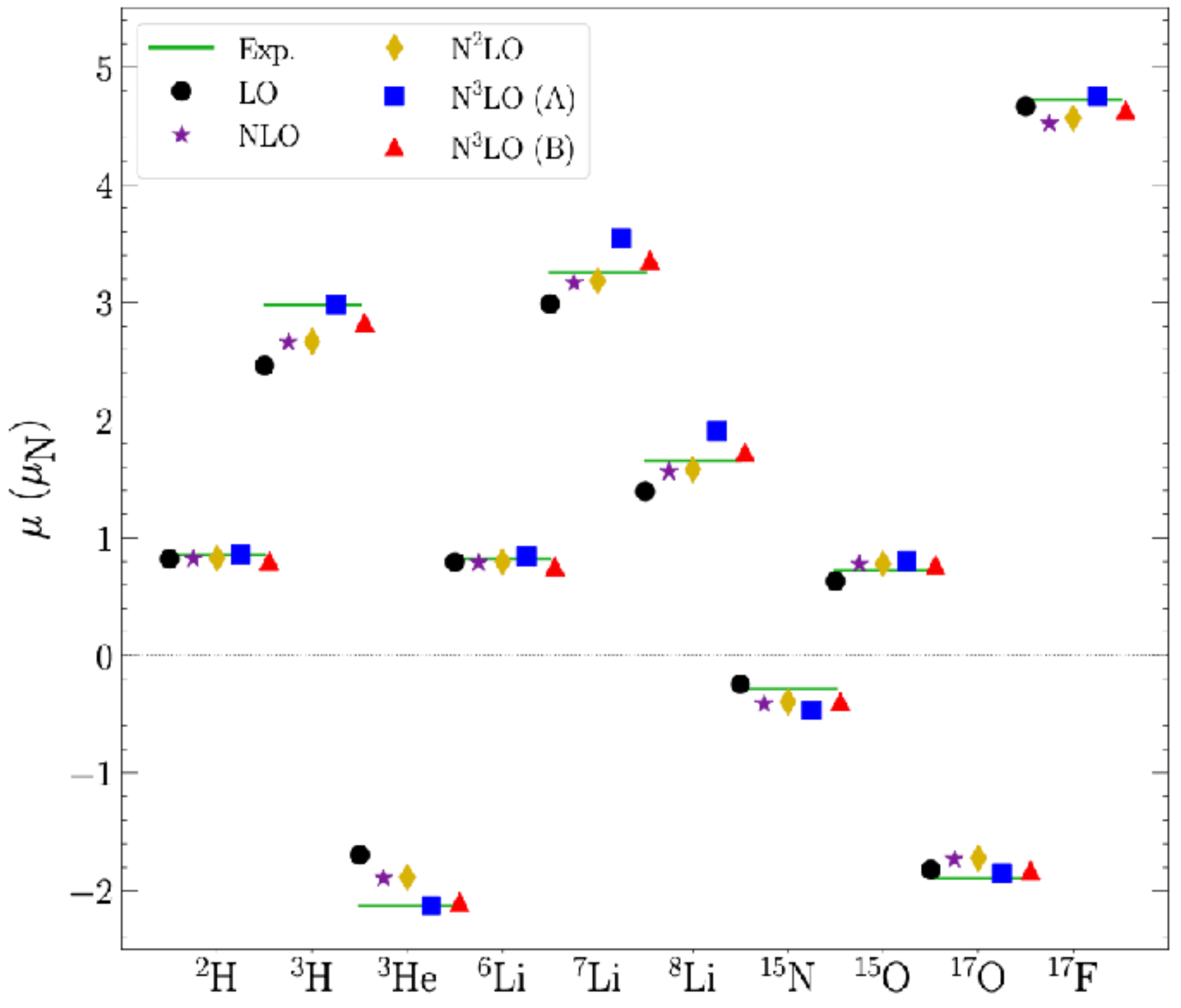
Using the magnetic moments

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)



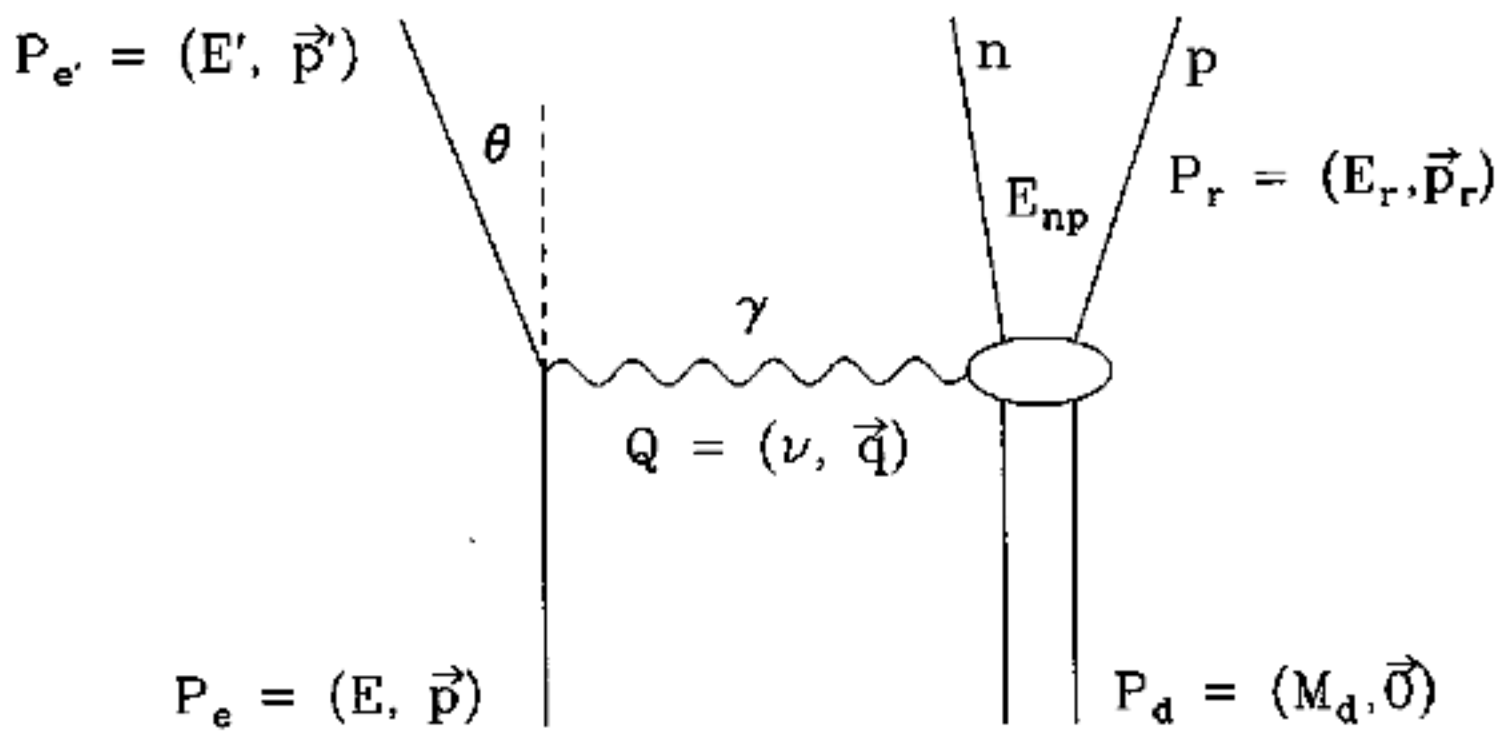
[J.D. Martin et al., PRC 108, L031304 (2023)]

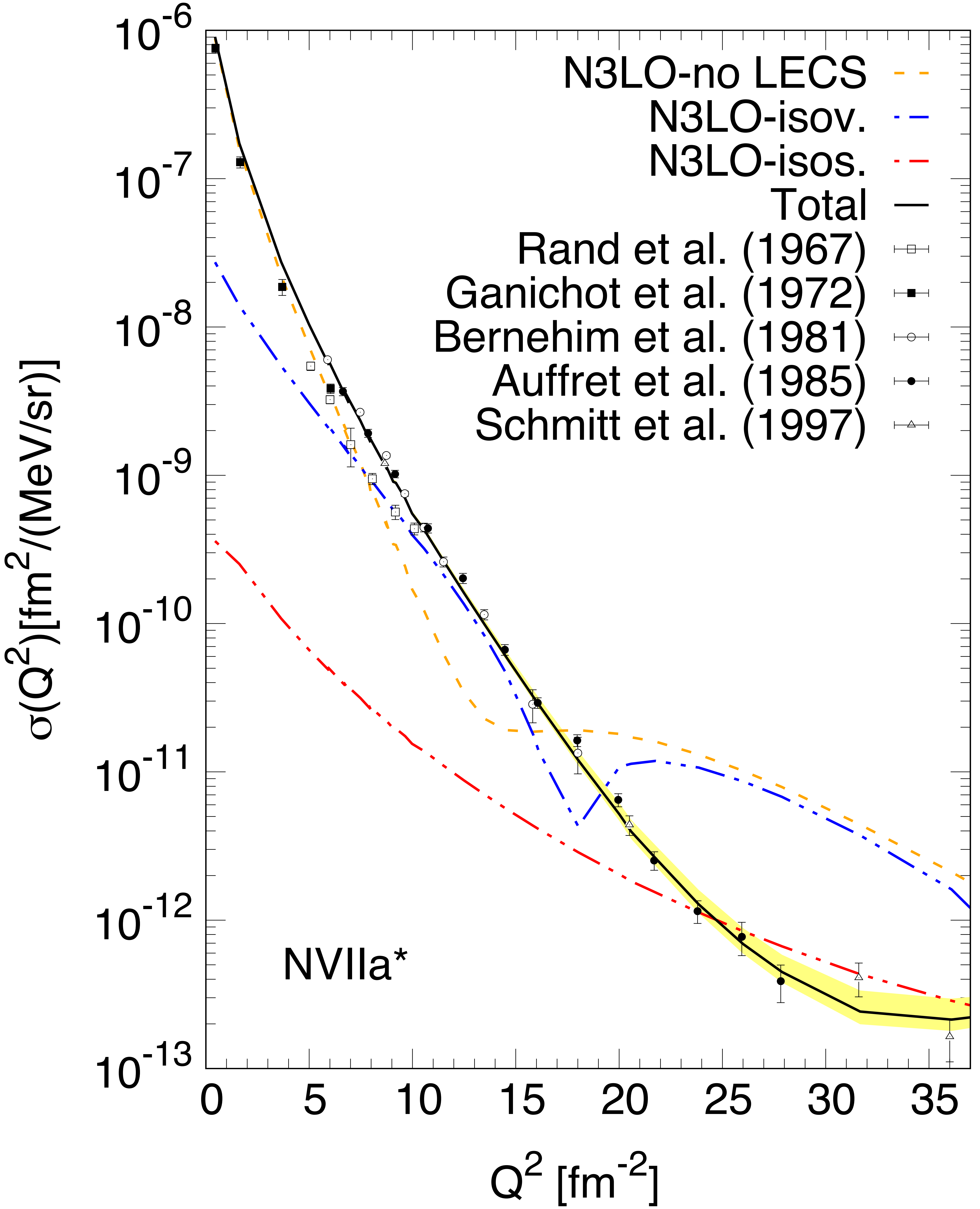
Diffraction generated by tensor forces

How to fix the LECs II

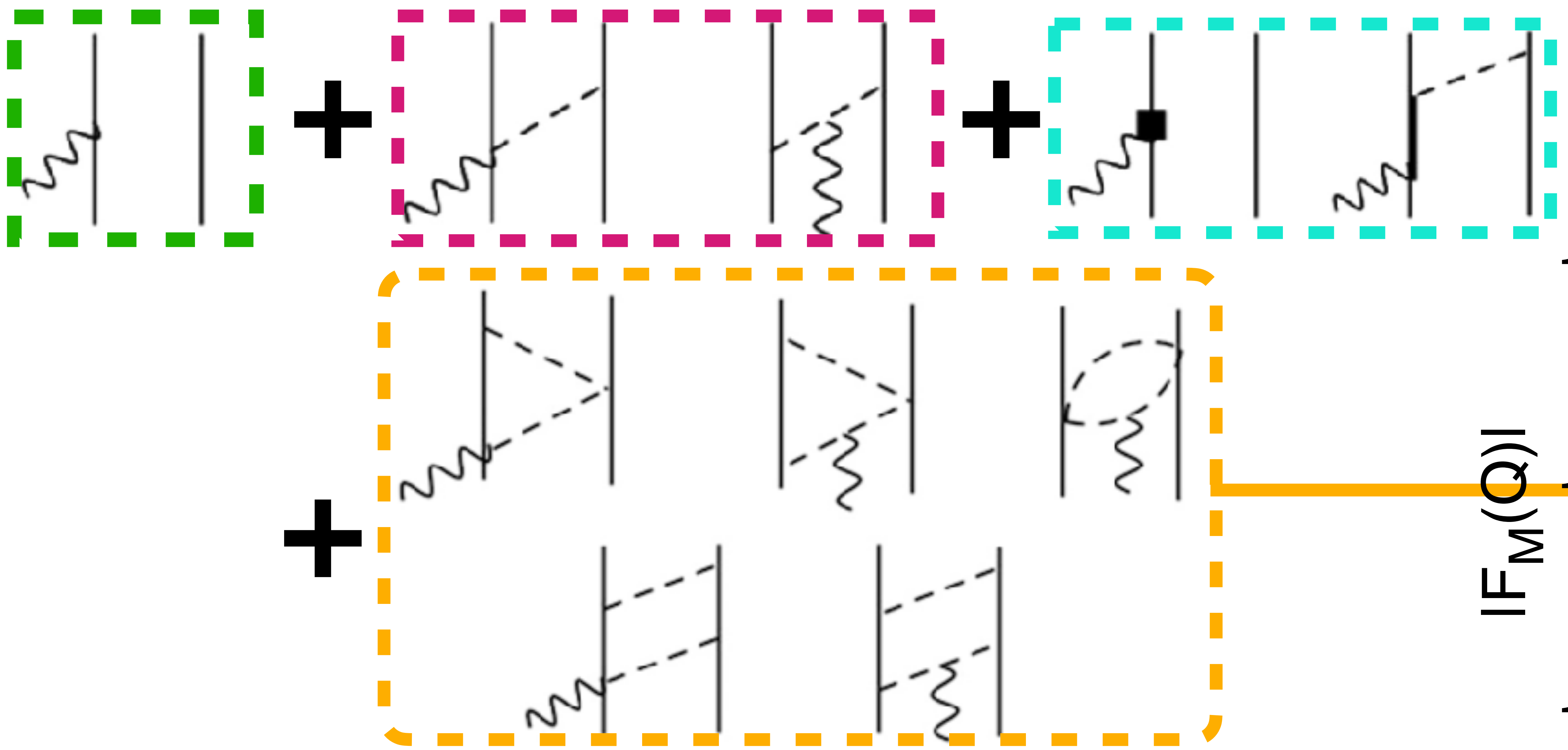
PRC 106, 04401 (2020)

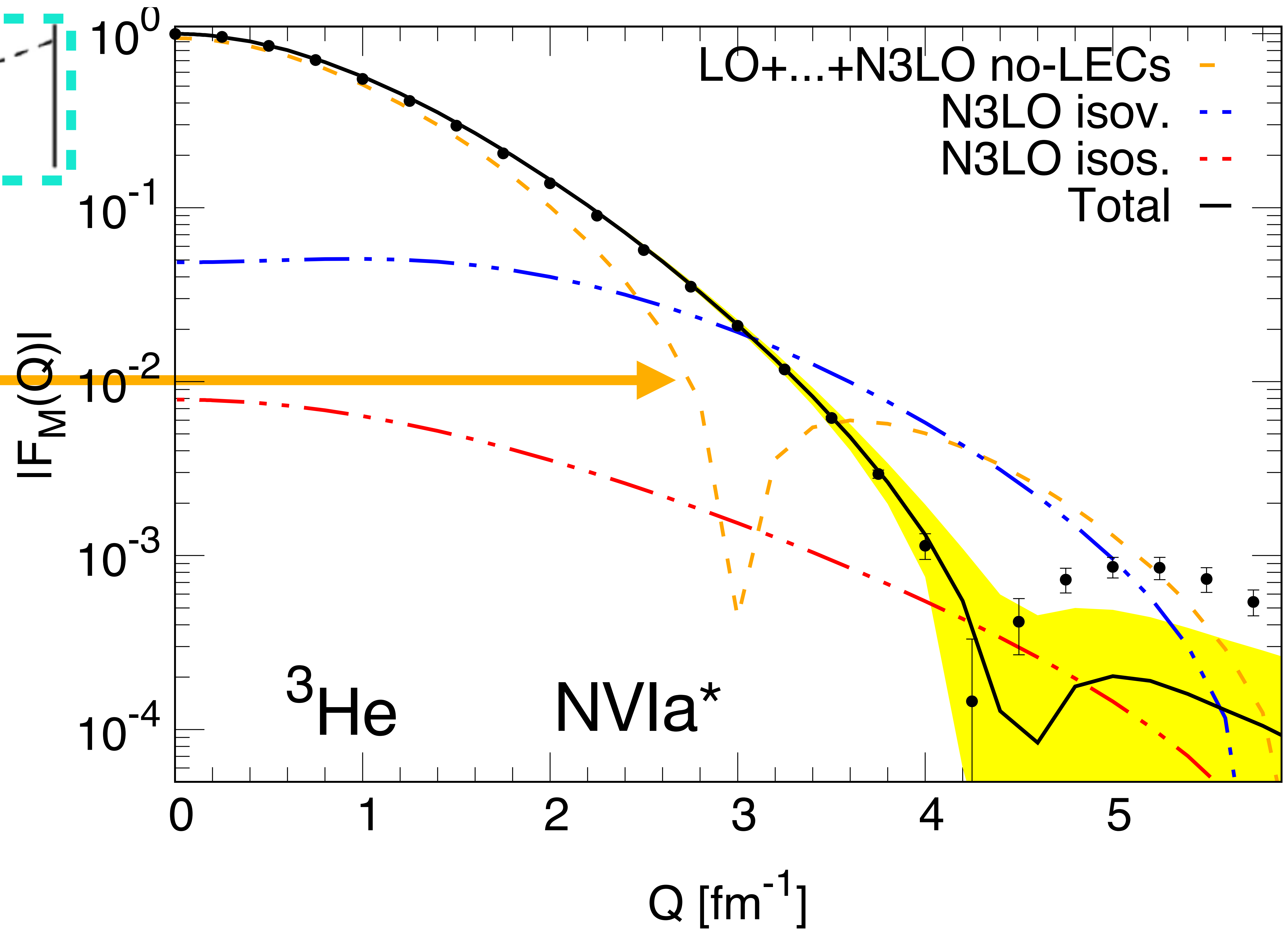
- Magnetic moments of d, ^{3}He, ^{3}H (fix normalization)
- Deuteron-threshold electrodisintegration at backward angles (fix dynamics)

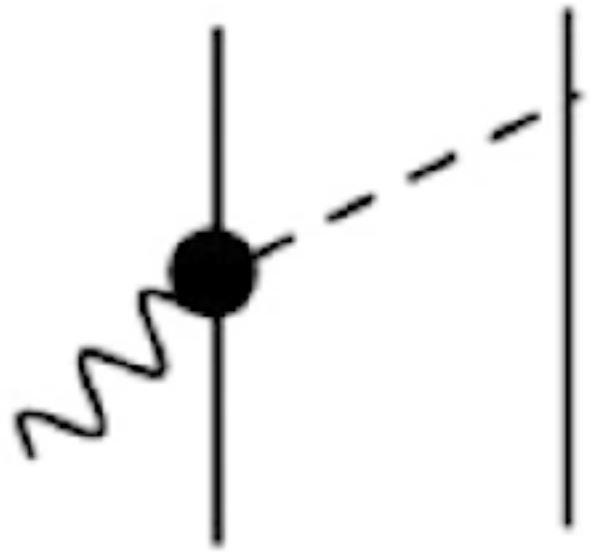




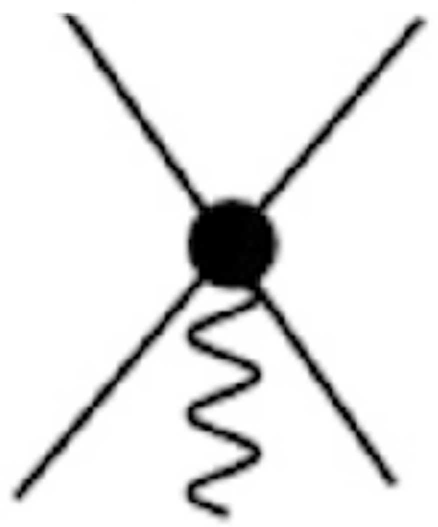
Prediction of A=3 Magnetic Form Factor







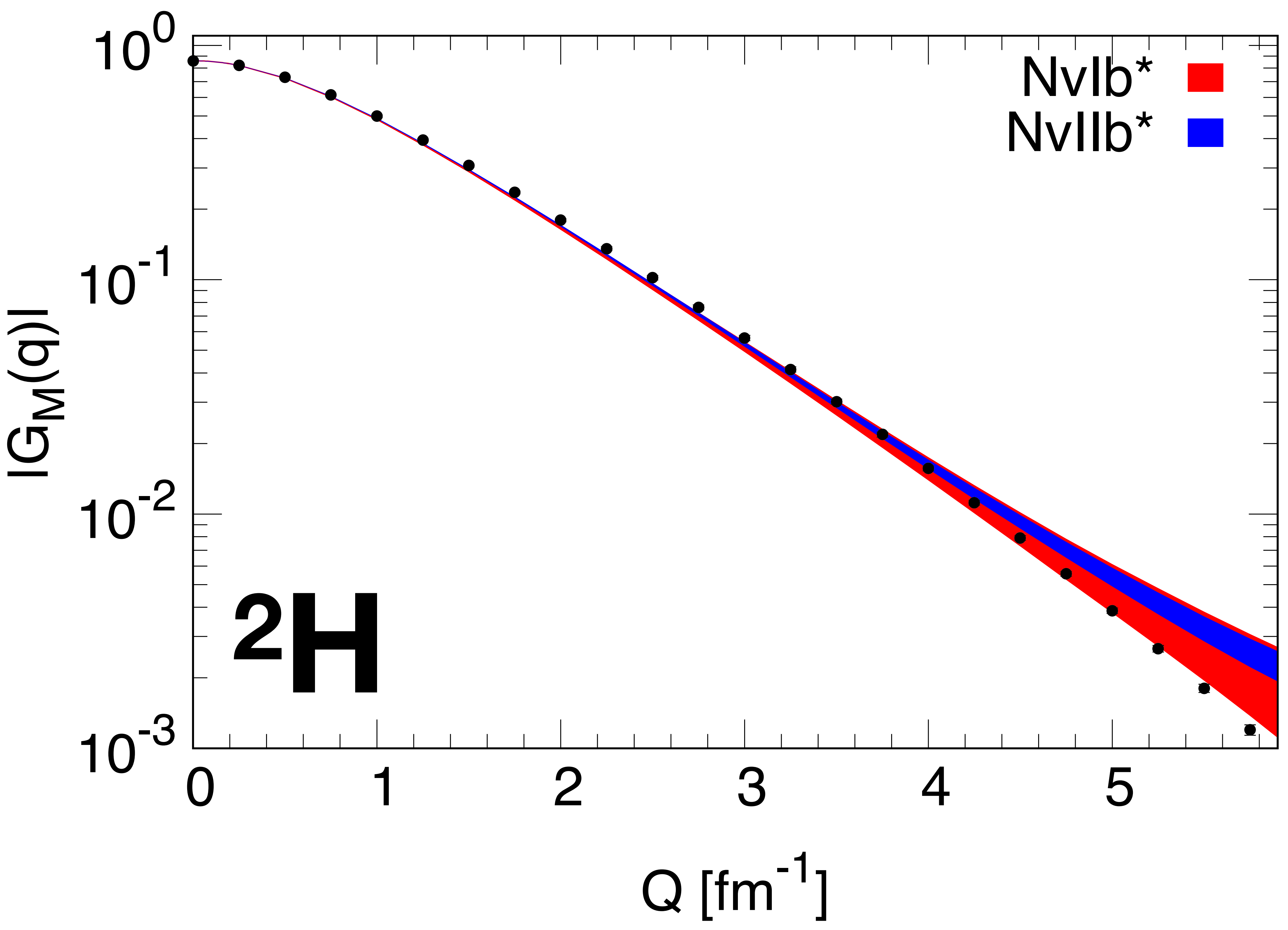
d_2^V d_3^V d_2^S

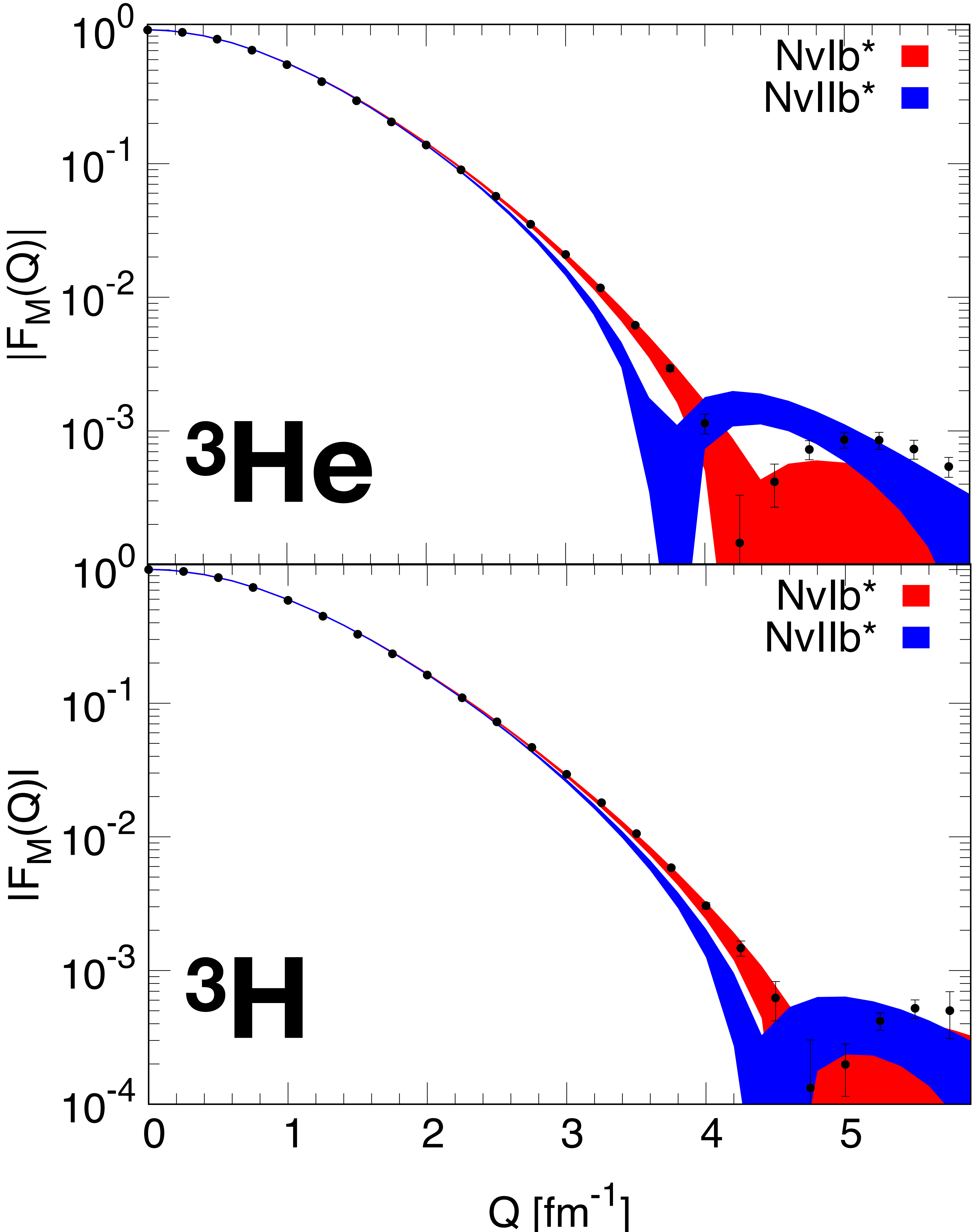


d_1^V d_1^S

The isovector components fill/generates the diffraction

Results for ^2H, ^3H, ^3He





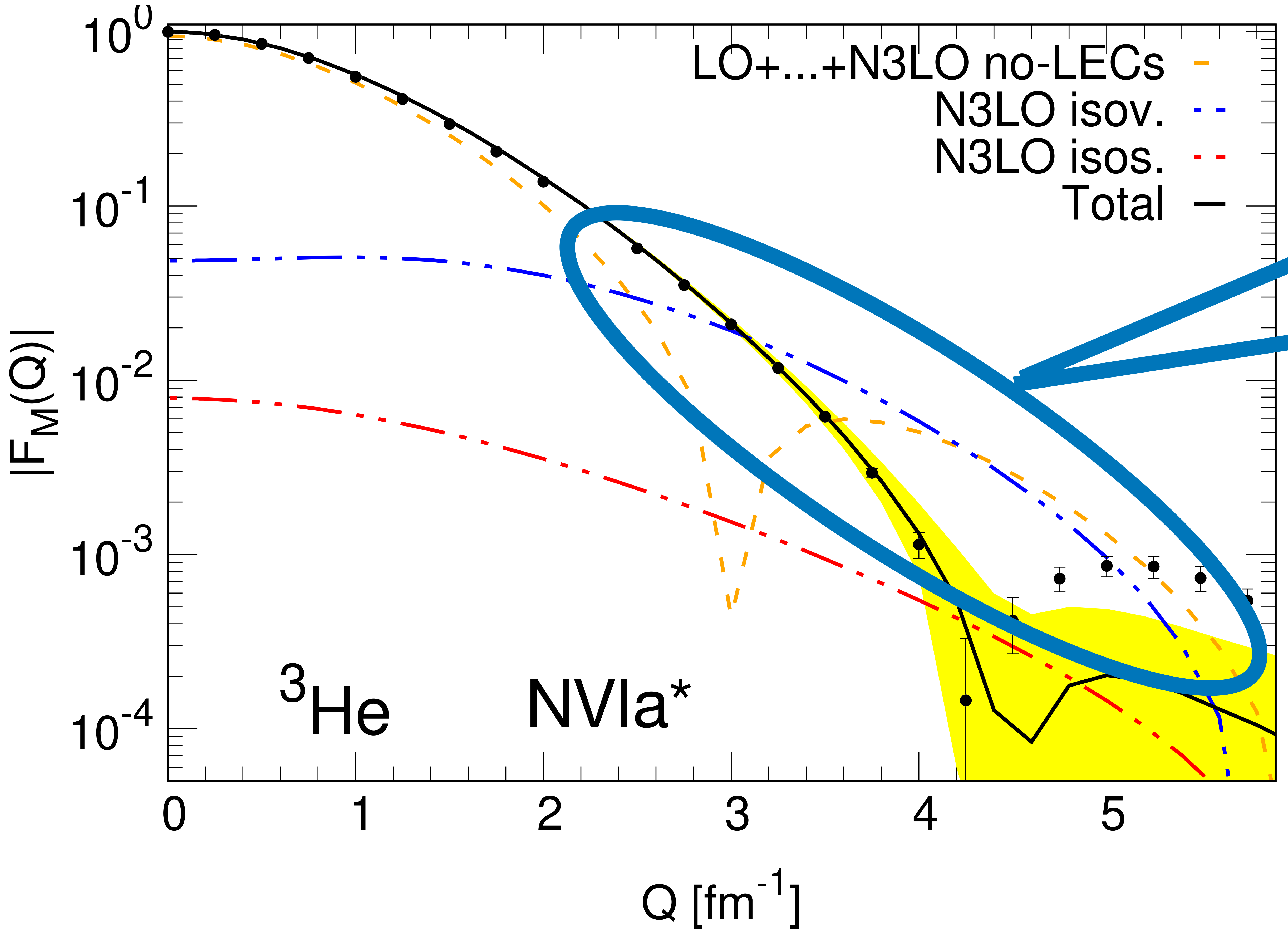
Norfolk interaction model

[M. Piarulli, et al., PRC 94, 054007 (2016)]

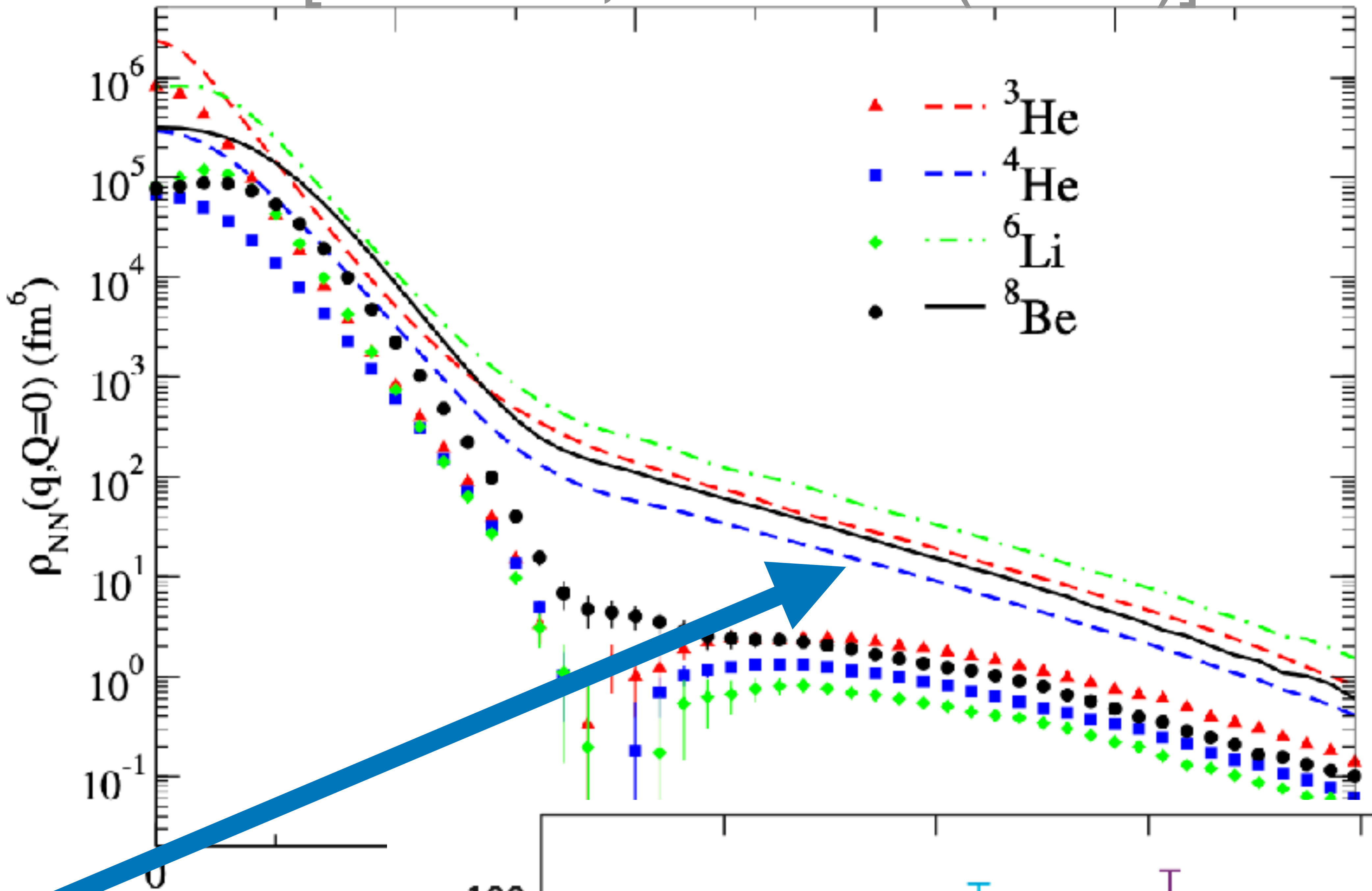
Why does it work?

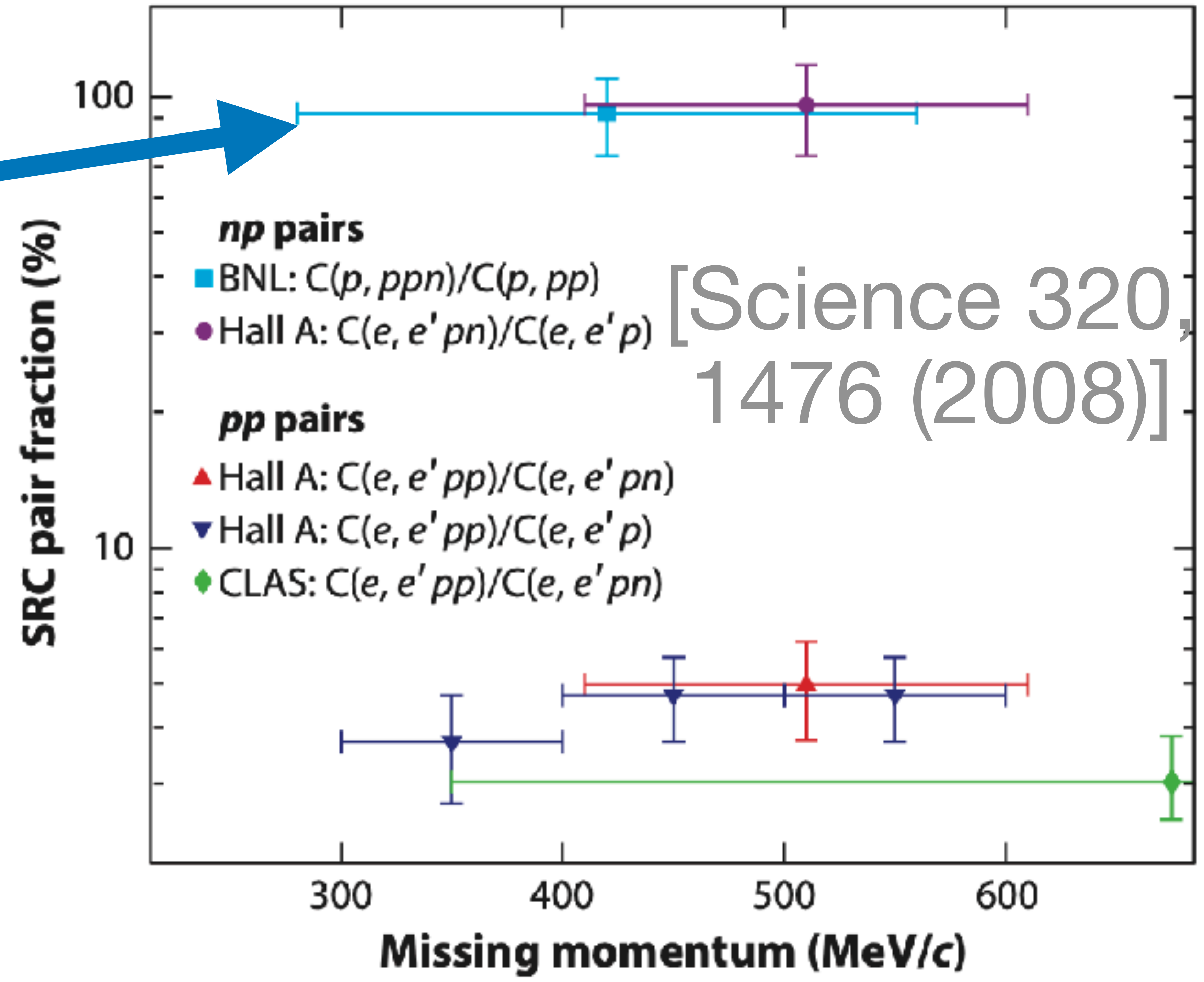
Isovector currents transform S/T=0/1 in S/T=1/0 pairs

np dominance



[PRL 98, 132501 (2007)]



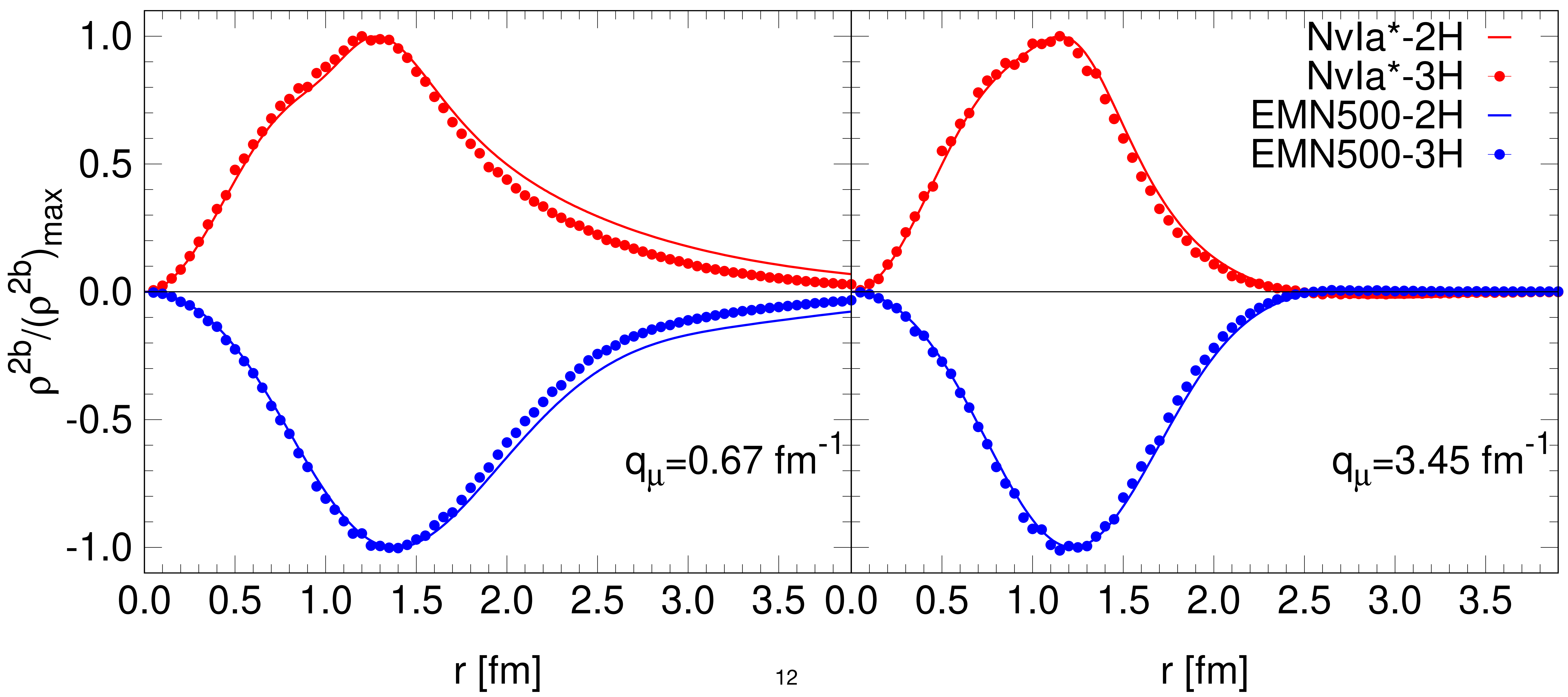


[Science 320, 1476 (2008)]

Why does it work?

Universal behavior of isovector transitions

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

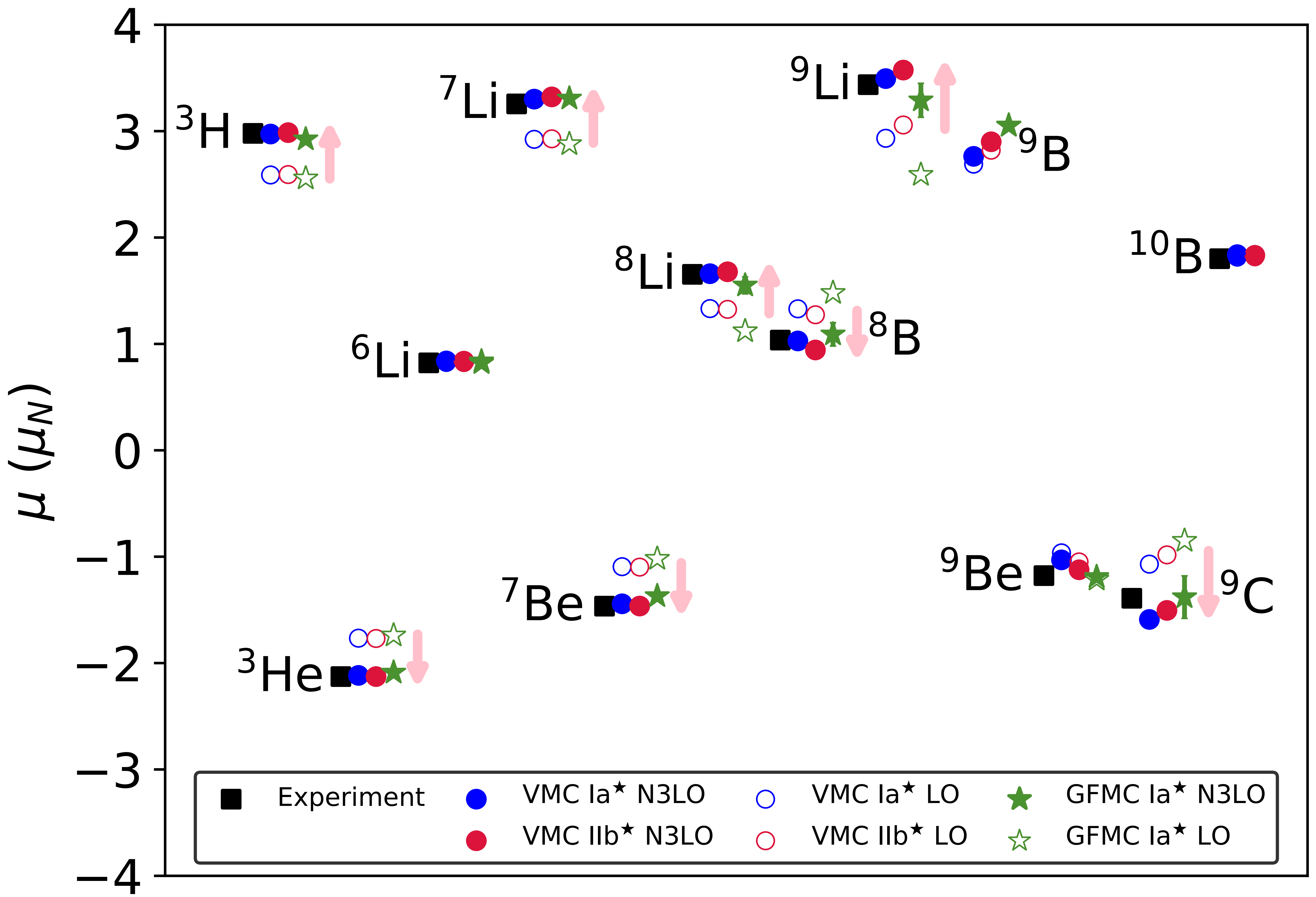


Magnetic moments of light nuclei

Magnetic structure at $Q = 0$

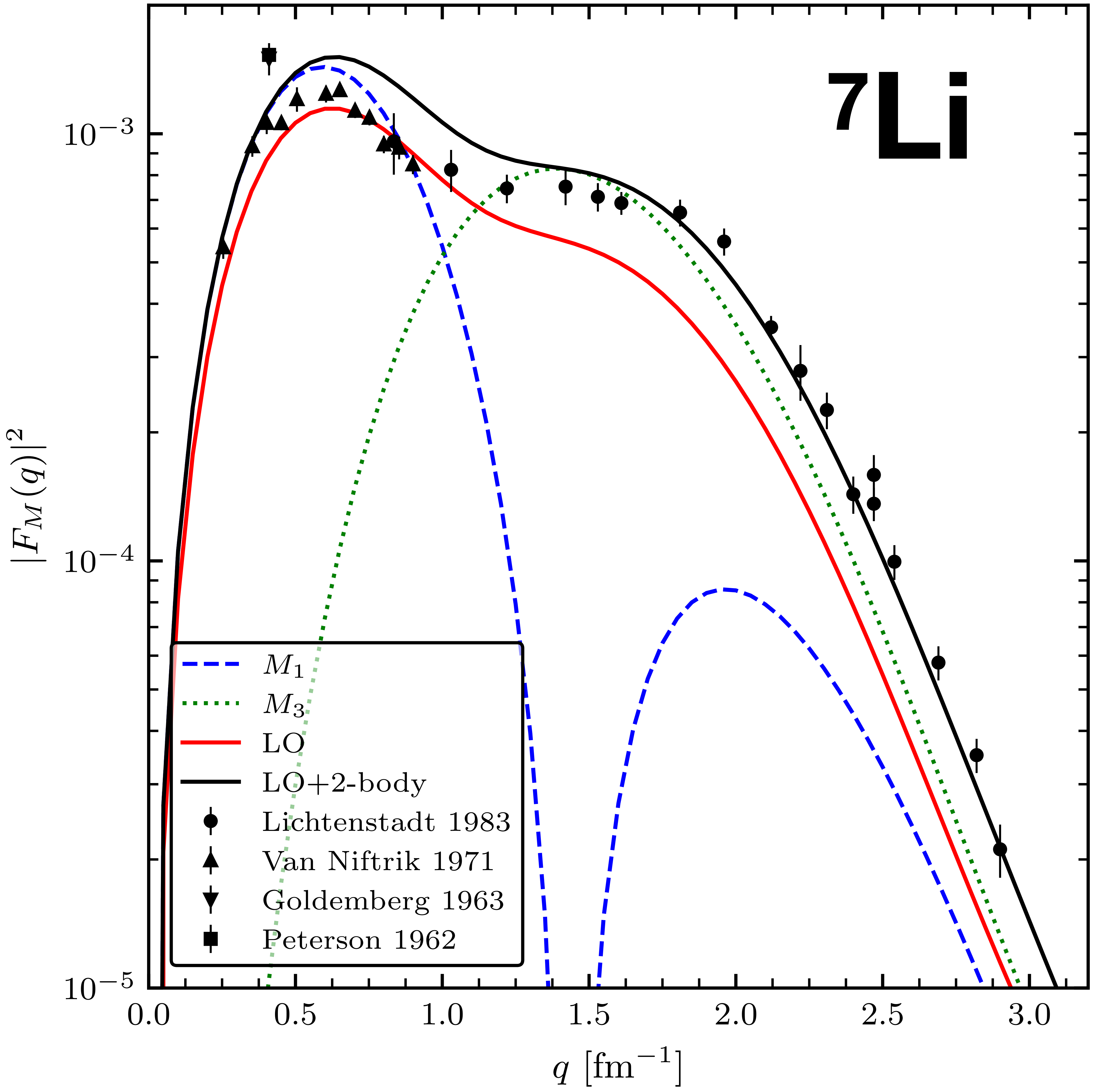
- Calculation performed using Variational Monte Carlo and Green Function Monte Carlo methods (see L. Andreoli talk).

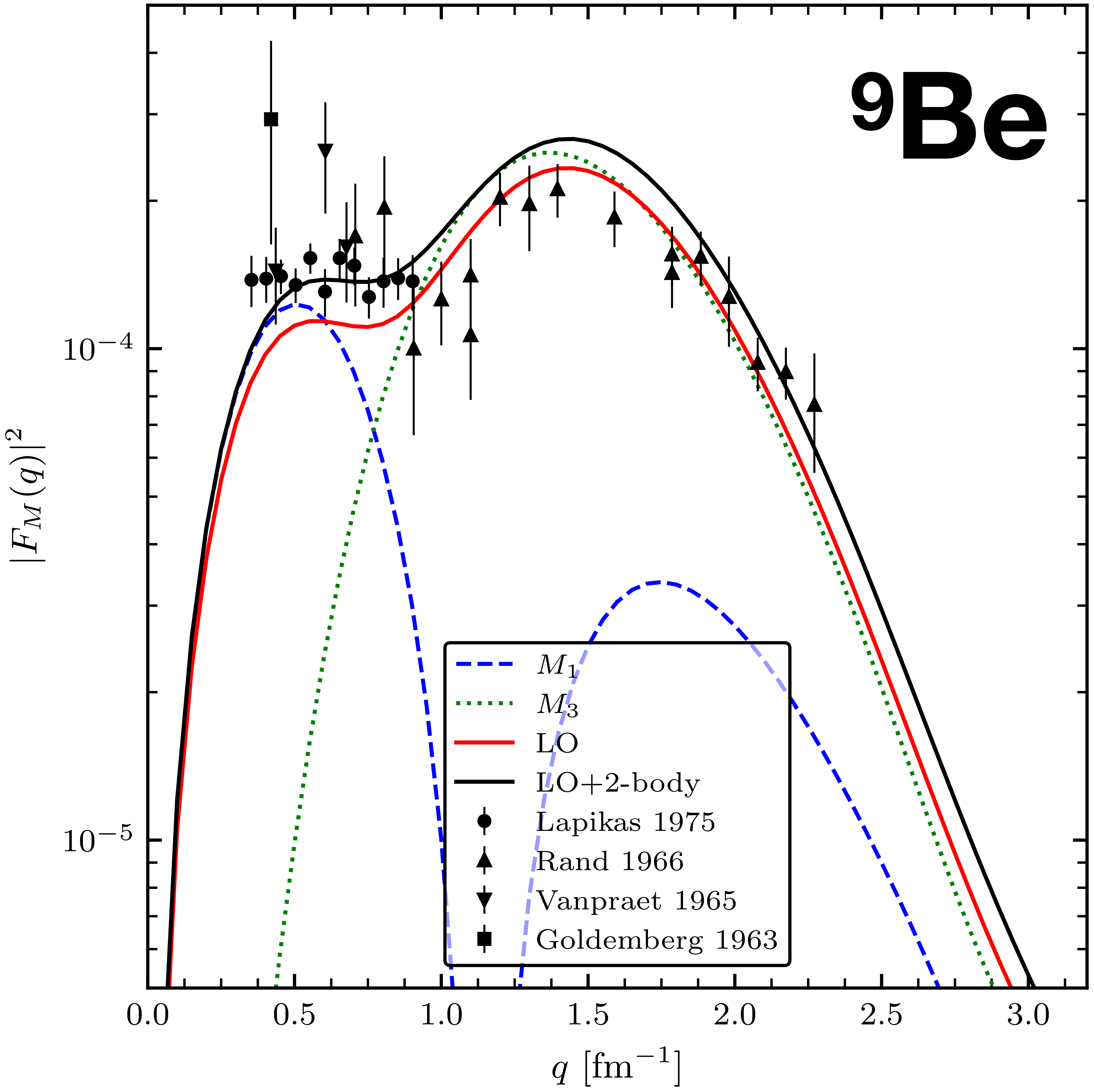
- The two-body currents bring the calculation in agreement with the experiments (pink arrows).



Magnetic form factor predictions

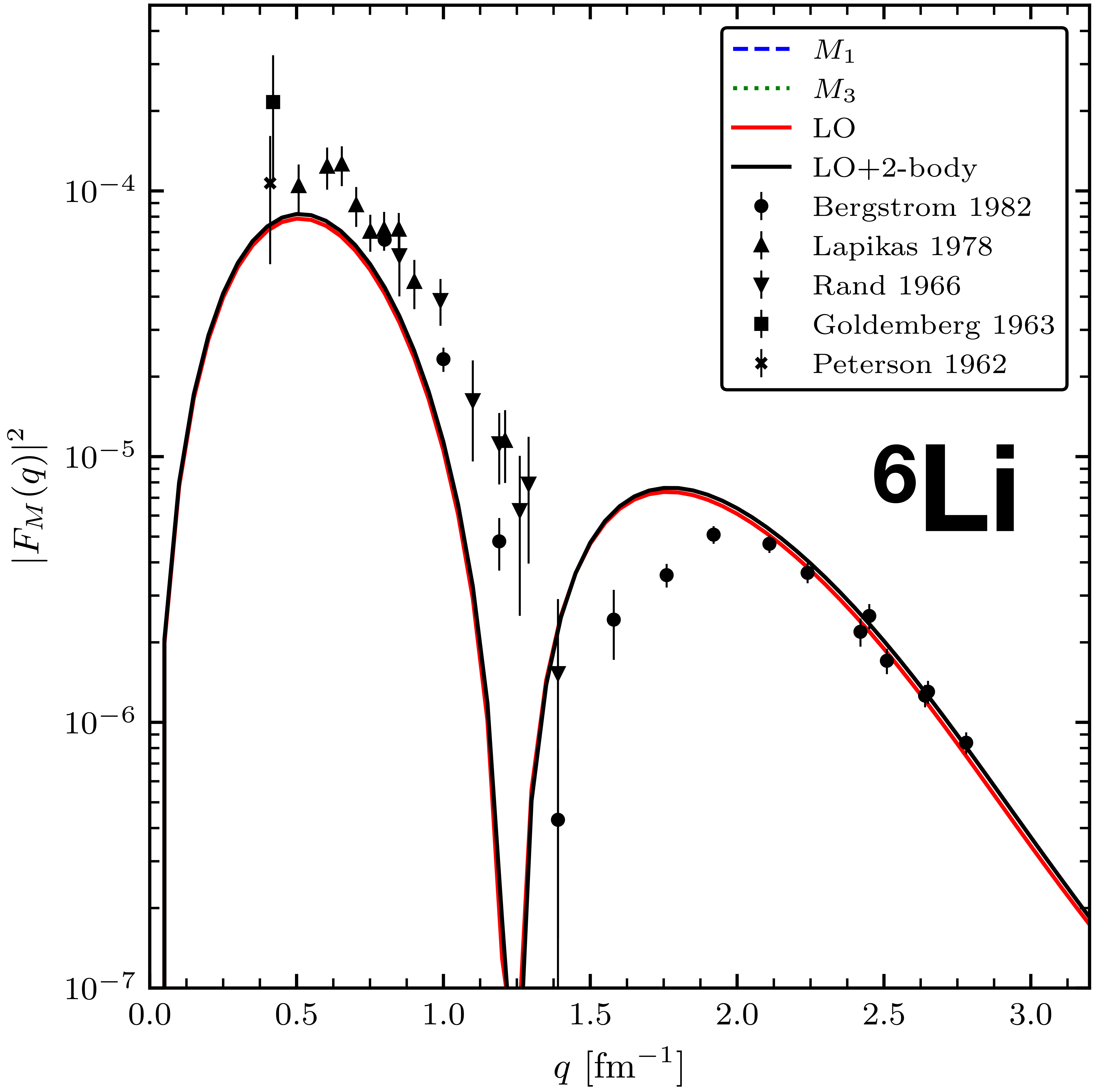
Lithium-7 and Berilium-9 (isovector dominated)

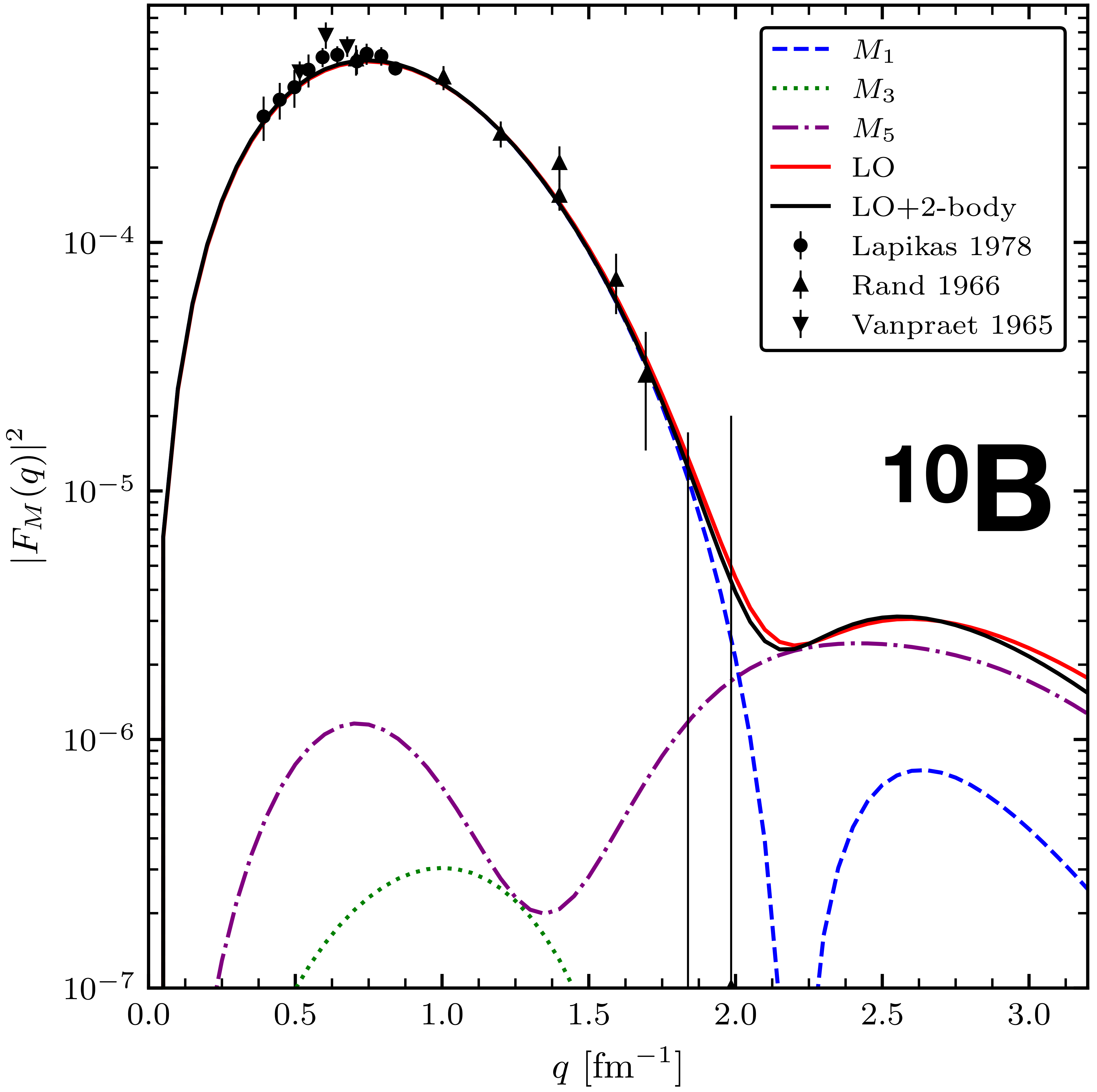




Magnetic form factor predictions

Lithium-6 and Boron-10 (isoscalar dominated)

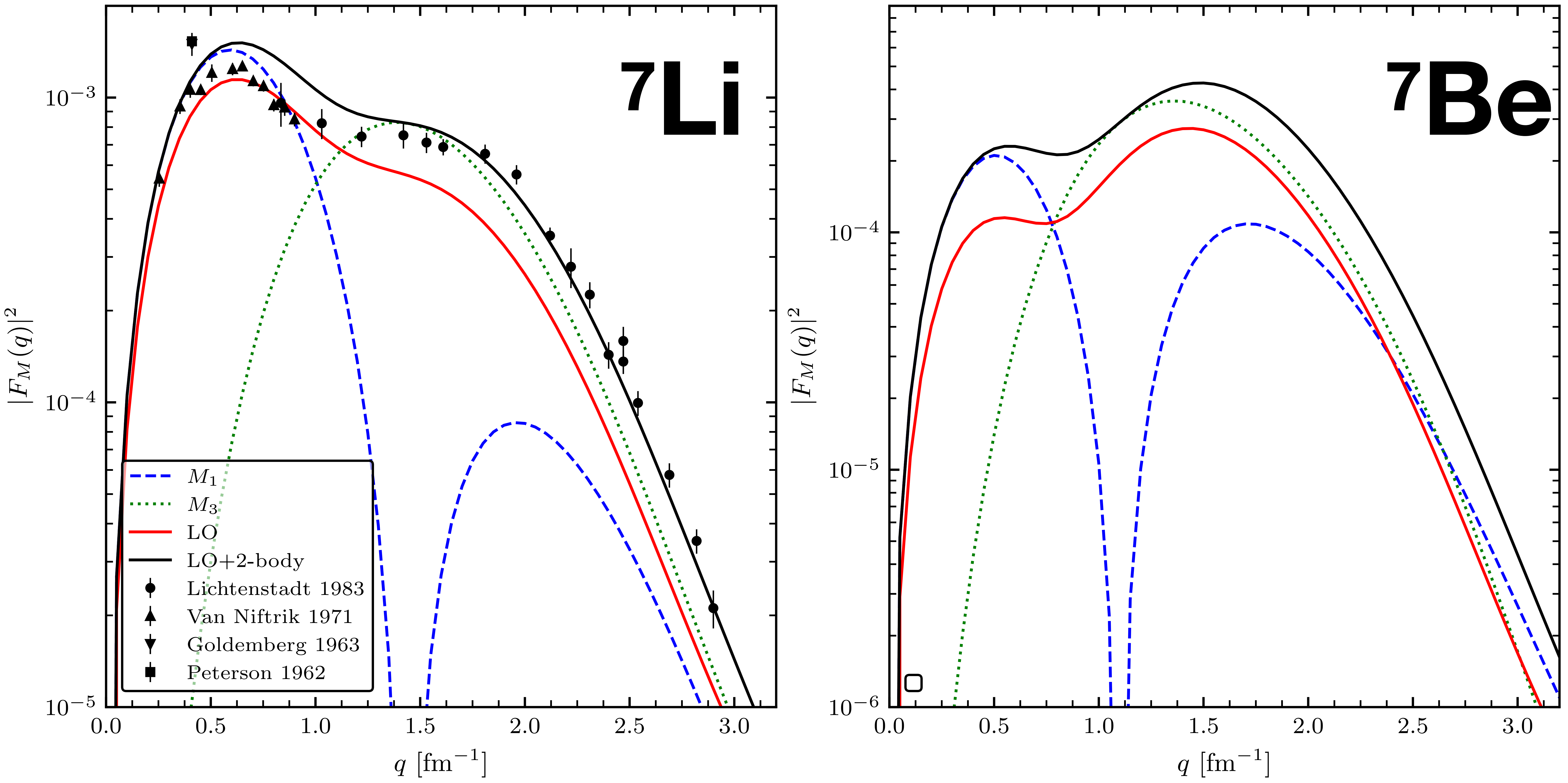




Mirror nuclei structure

- M_1 is enhanced respect to M_3 for nuclei with an unpaired neutron in the p-shell.

- We observed a similar phenomenon for the mirror systems ^{9}Li-^{9}C and ^{9}Be-^{9}B



Pure prediction (no previous literature) + no experimental confirmation

Mirror nuclei structure

The reason

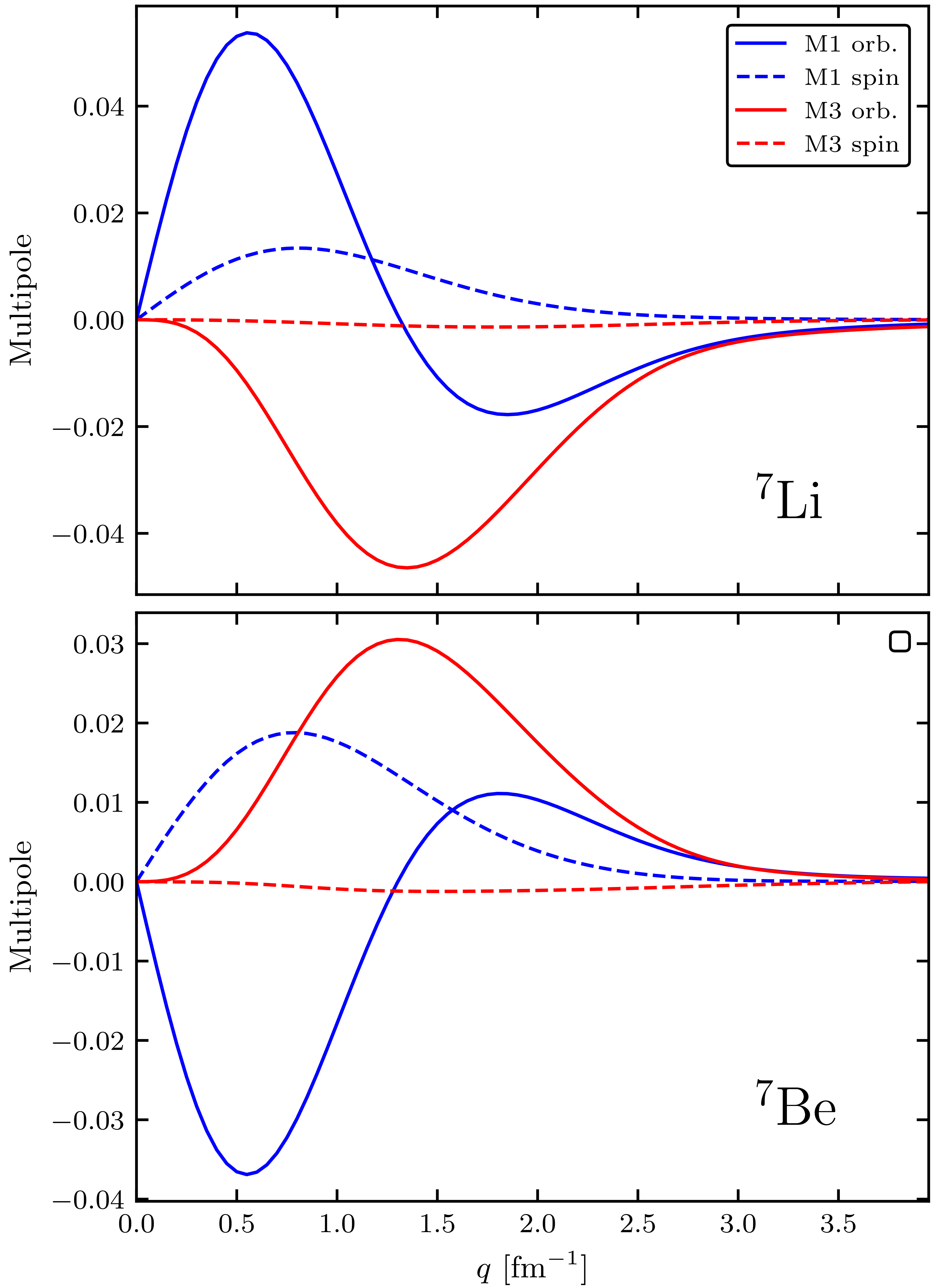
$$\mathbf{j}^{\mathrm{LO}}(\mathbf{q}) = \frac{\epsilon_i(q_\mu^2)}{2\,m}\,\left[\mathbf{p}_i\,,\,\mathrm{e}^{i\mathbf{q}\cdot\mathbf{r}_i}\right]_+ + i\,\frac{\mu_i(q_\mu^2)}{2\,m}\,\mathrm{e}^{i\mathbf{q}\cdot\mathbf{r}_i}\,\sigma_i\times\mathbf{q}\,,$$

Convection current

Magnetic current

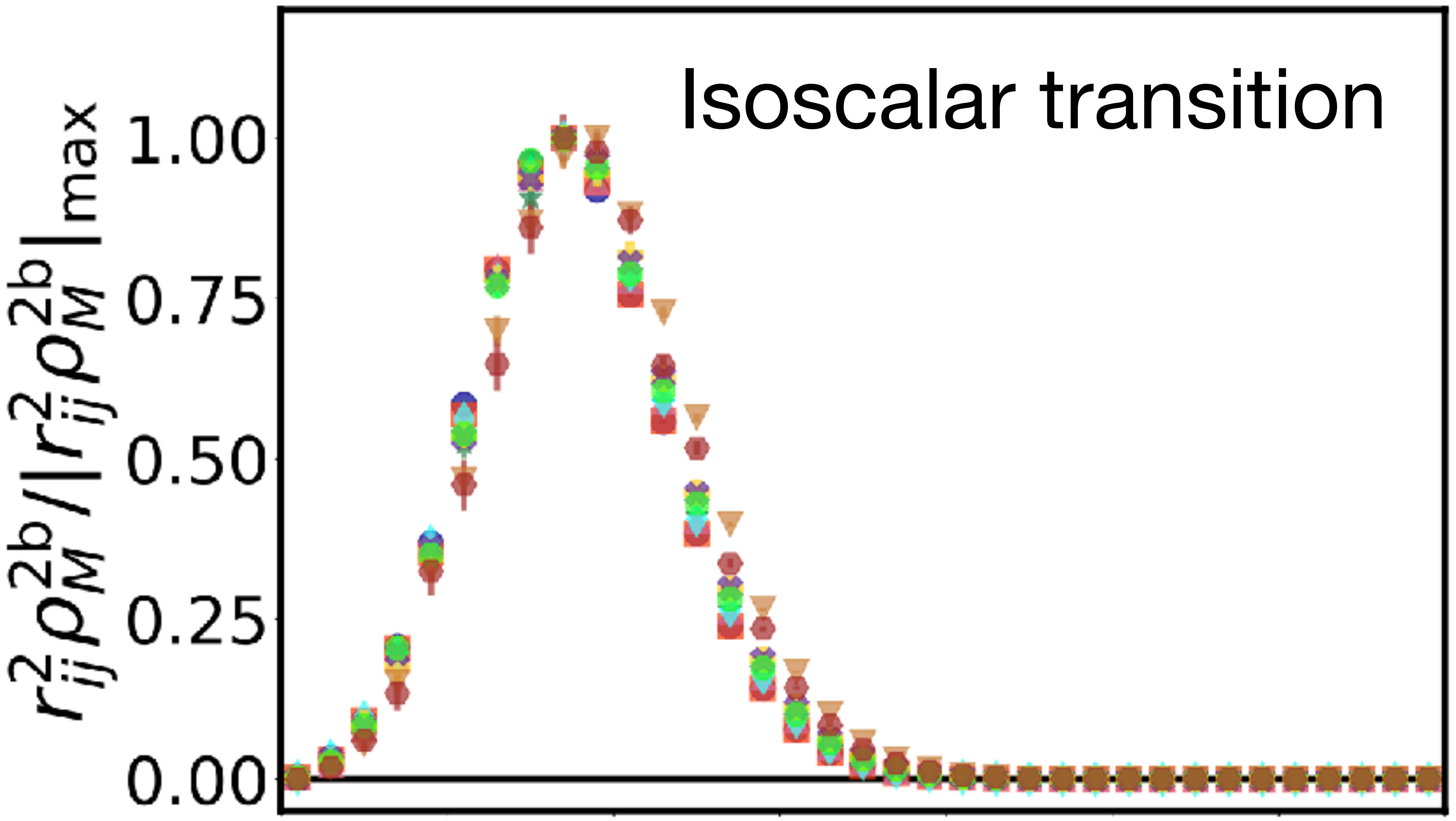
No contribution to M_3

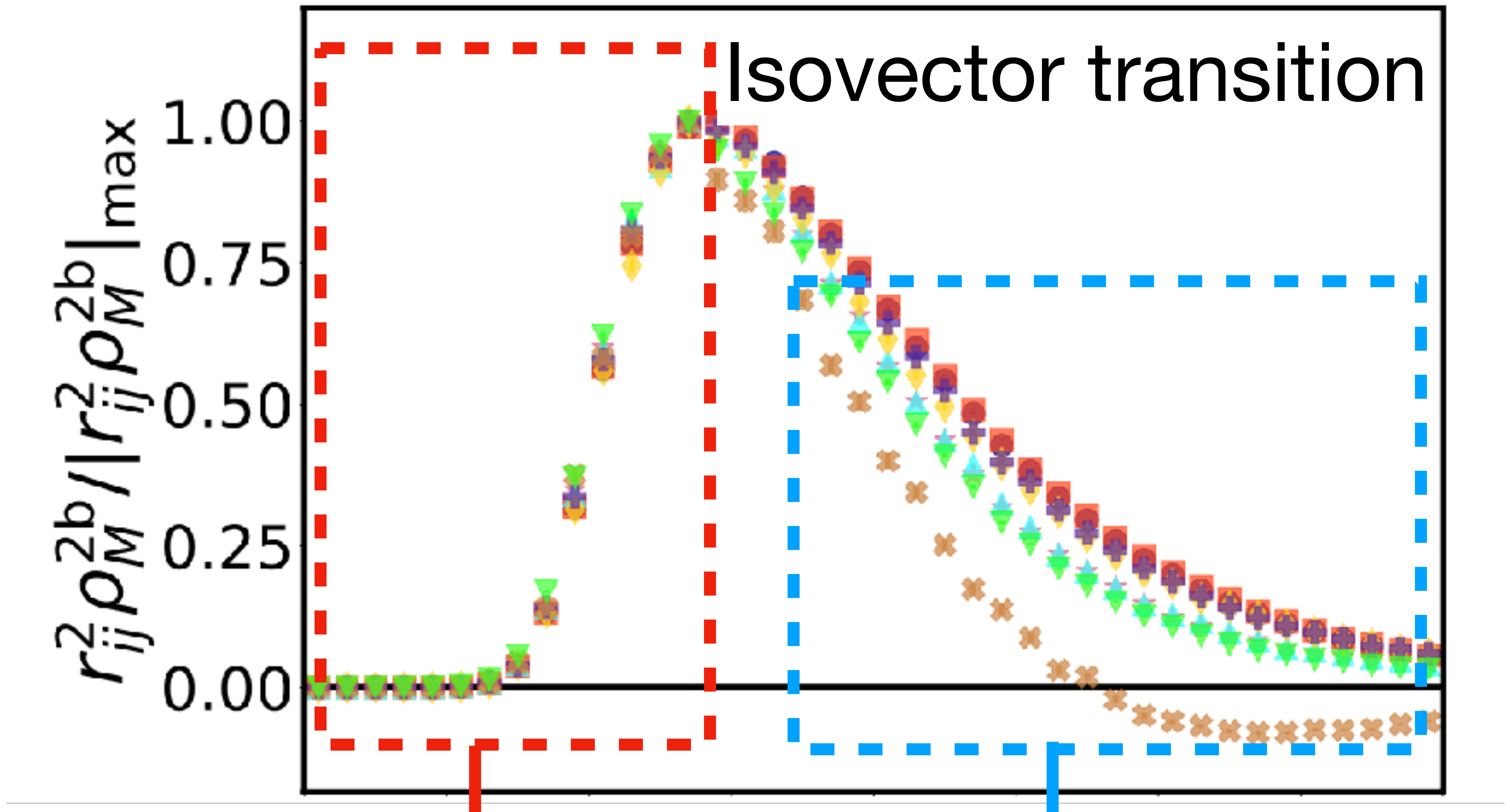
Change sign if there is an unpaired neutron/proton



More on 2-body transition densities

Universality of isoscalar and isovector transitions





Transition $^1S_0 \leftrightarrow {}^1S_0 \quad {}^3S_1 \leftrightarrow {}^3S_1$

ST=00 isoscalar couples suppressed

SRC $^1S_0 \leftrightarrow {}^3S_1$

P-waves + ST=11 isovector couples

Summary

Magnetic form factors

- First ab-initio calculation of magnetic form factors of nuclei up to A=10.
- Good description of available magnetic form factor data.

- **Two-body currents account up to 40-50% of the total contribution to the magnetic form factors.**
- **First observation of M_1/M_3 inversion in mirror p-shell nuclei (not observed experimentally yet).**

More data at larger Q^2 and on more nuclei would permit to validate our models

Conclusions

- Two-body currents are crucial for describing the EM structure of nuclei at $Q^2 \sim 0 - 0.64$ GeV^2
- The physics associated with the two body currents is determined by the correlations of nucleons in nuclei (SRC).
- The aim use the same currents and description of the nuclear dynamics to predict the effects in JLab experiments.
  - Increase the range of applicability (enlarge Q^2).
  - Integrate our calculation with higher energies model.
- **Discriminate between nuclear structure effects and pure nucleon physics**

Collaborators

L. Andreoli (JLab & ODU)

G. Chambers-Wall (WashU)

G. B. King (WashU)

S. Pastore (WashU)

M. Piarulli (WashU)

R. Schiavilla (JLab & ODU)

R. B. Wiringa (ANL)

Acknowledgments

NTNP
DOE Topical Collaboration

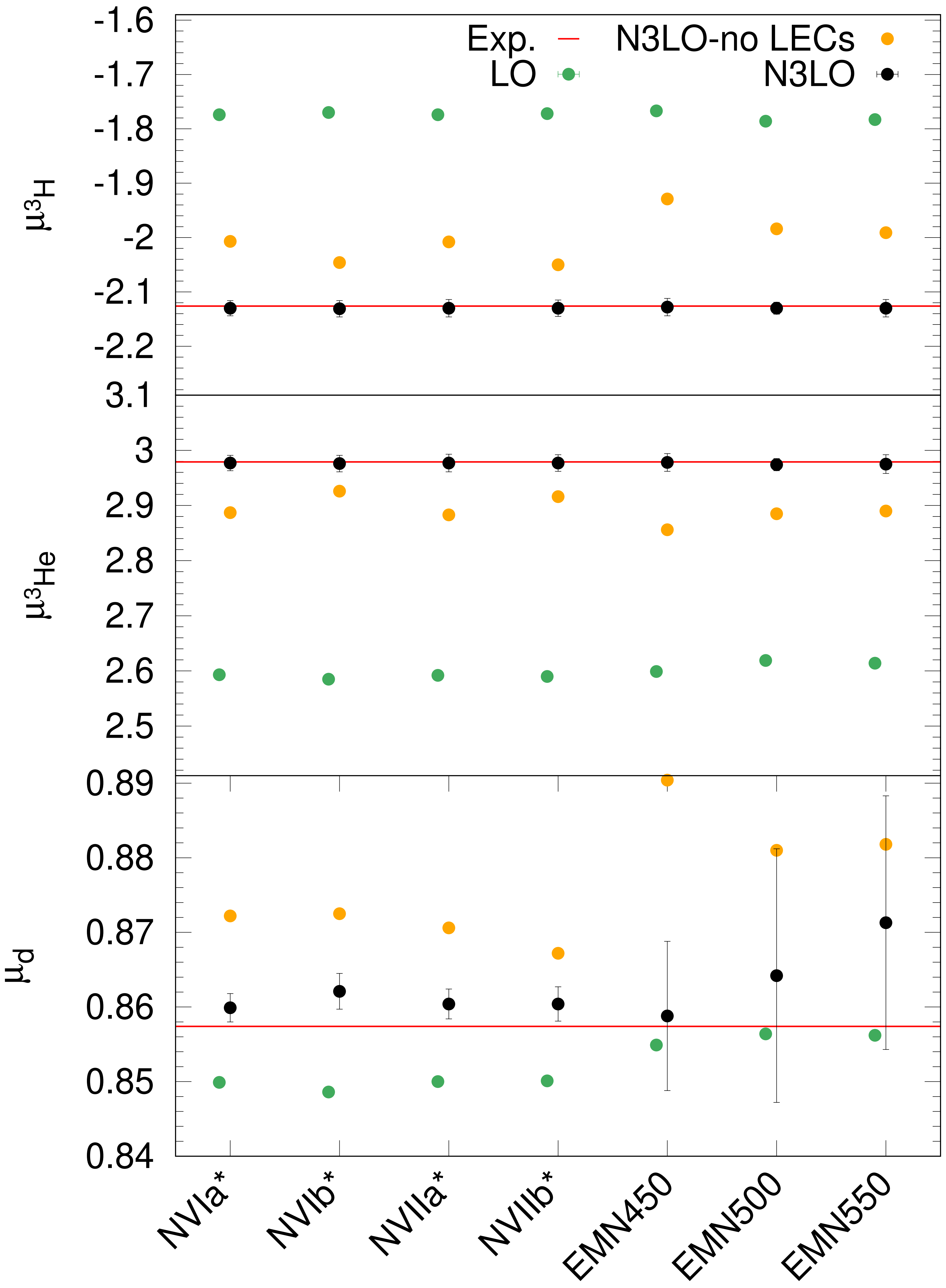
U.S. DEPARTMENT OF ENERGY

Sparse

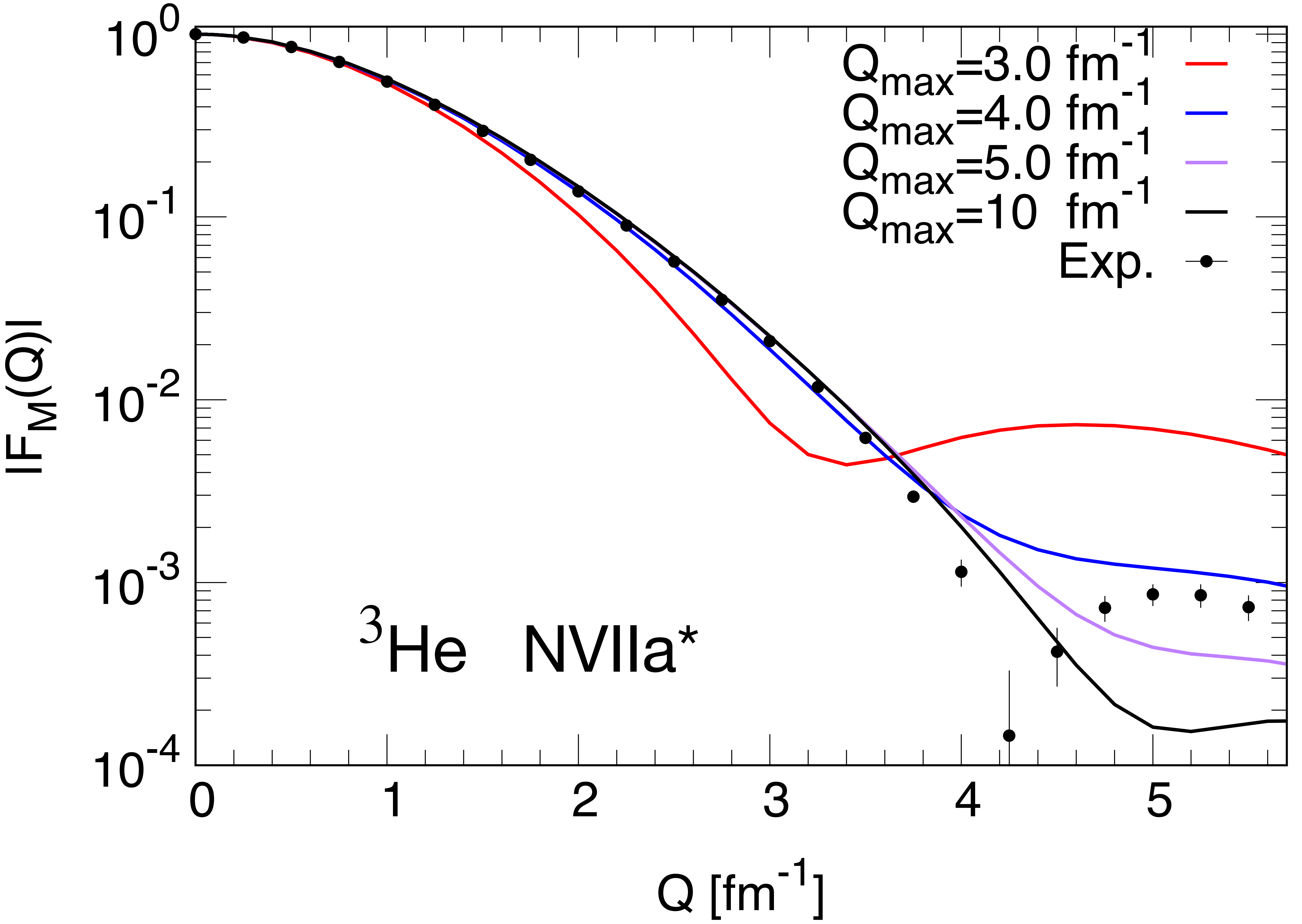
Results of the fit

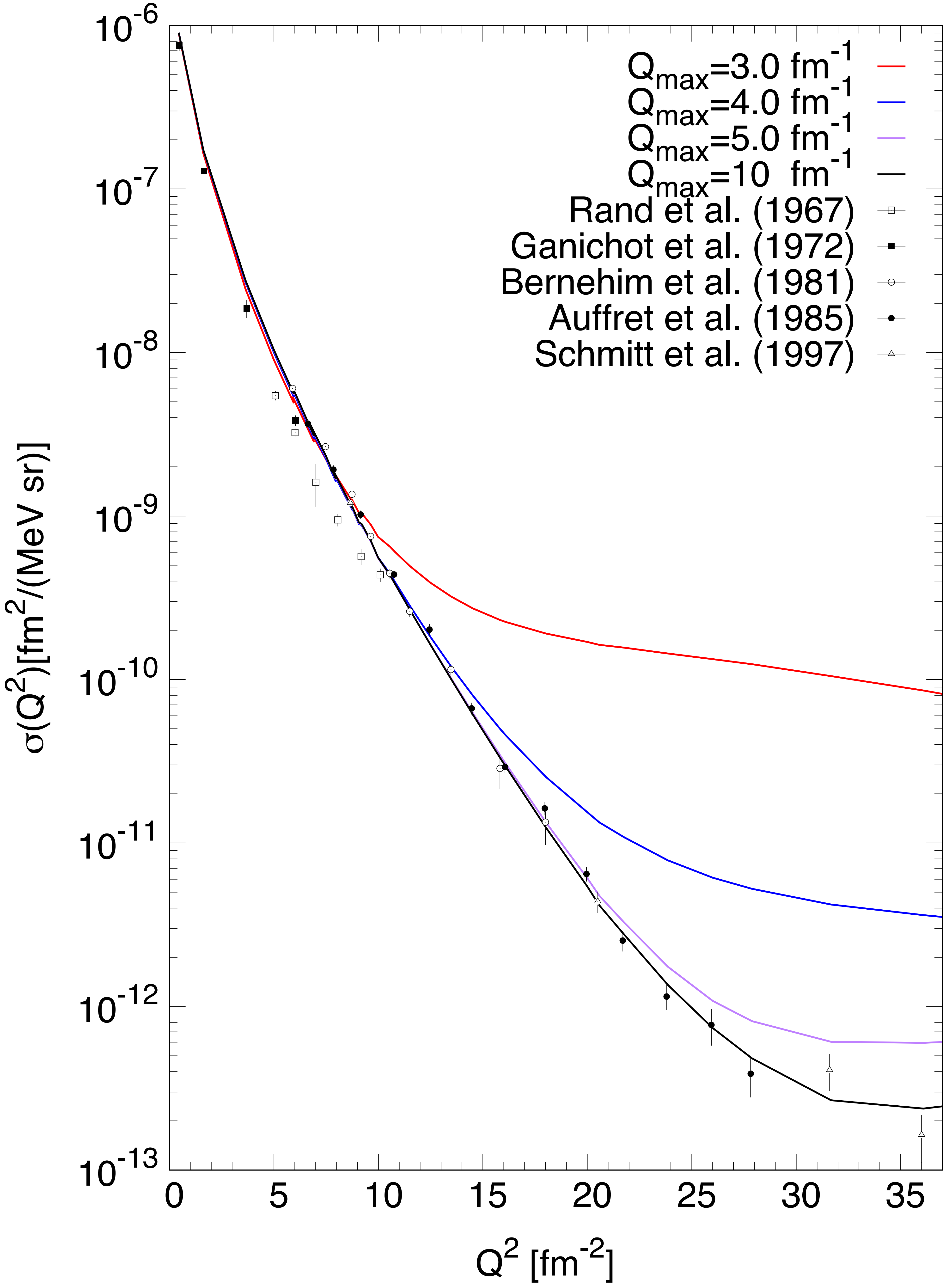
Pot.	χ^2/ndf	χ^2/ndf (no Rand)
NVIa*	9.9	2.0
NVIb*	10.2	2.3
NVIIa*	11.6	2.5
NVIIb*	11.6	2.6
EMN450	11.3	2.8
EMN500	14.7	4.7
EMN550	17.7	7.9

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

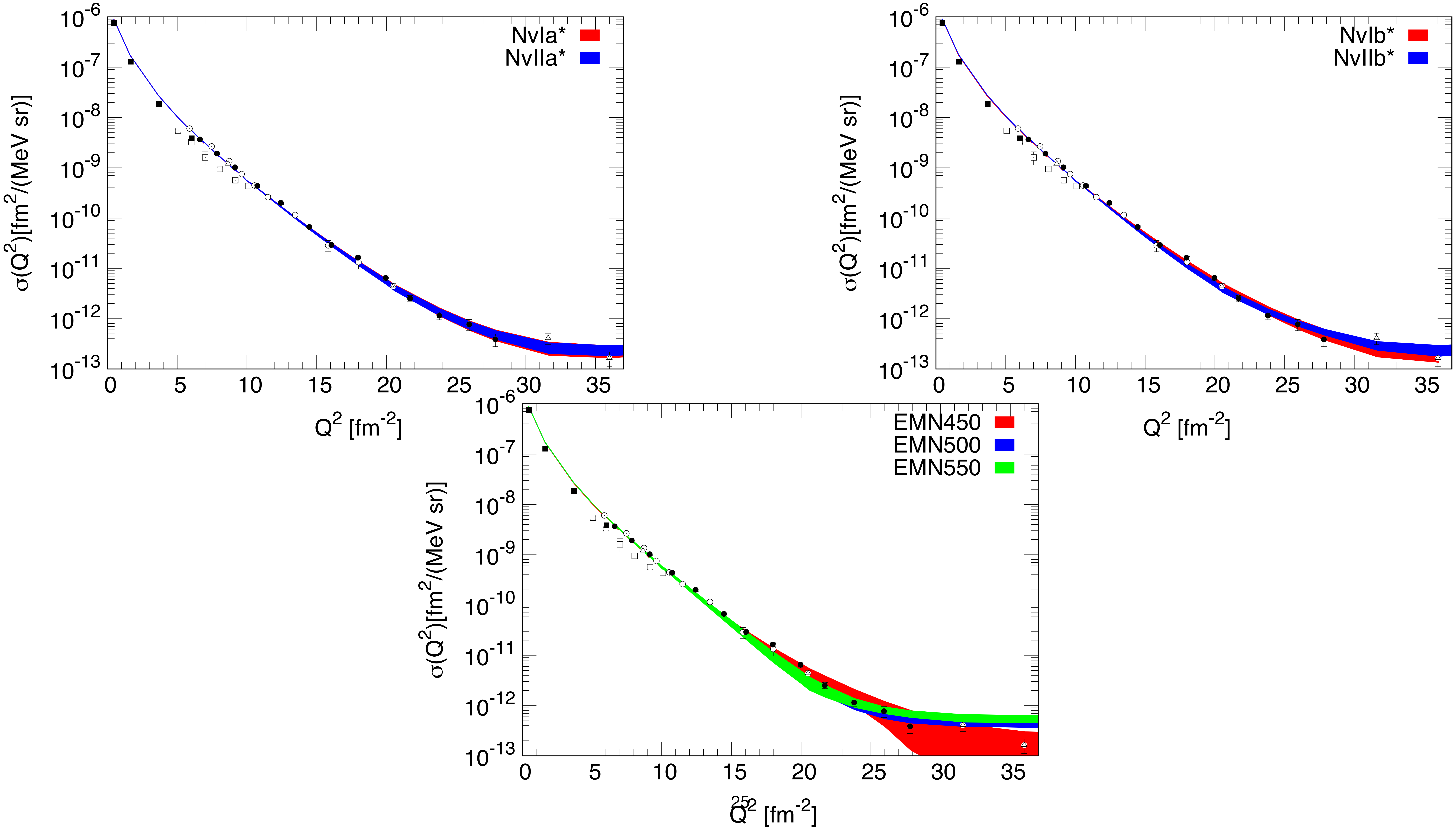


Dependence on $Q^2_{\mathbf{max}}$



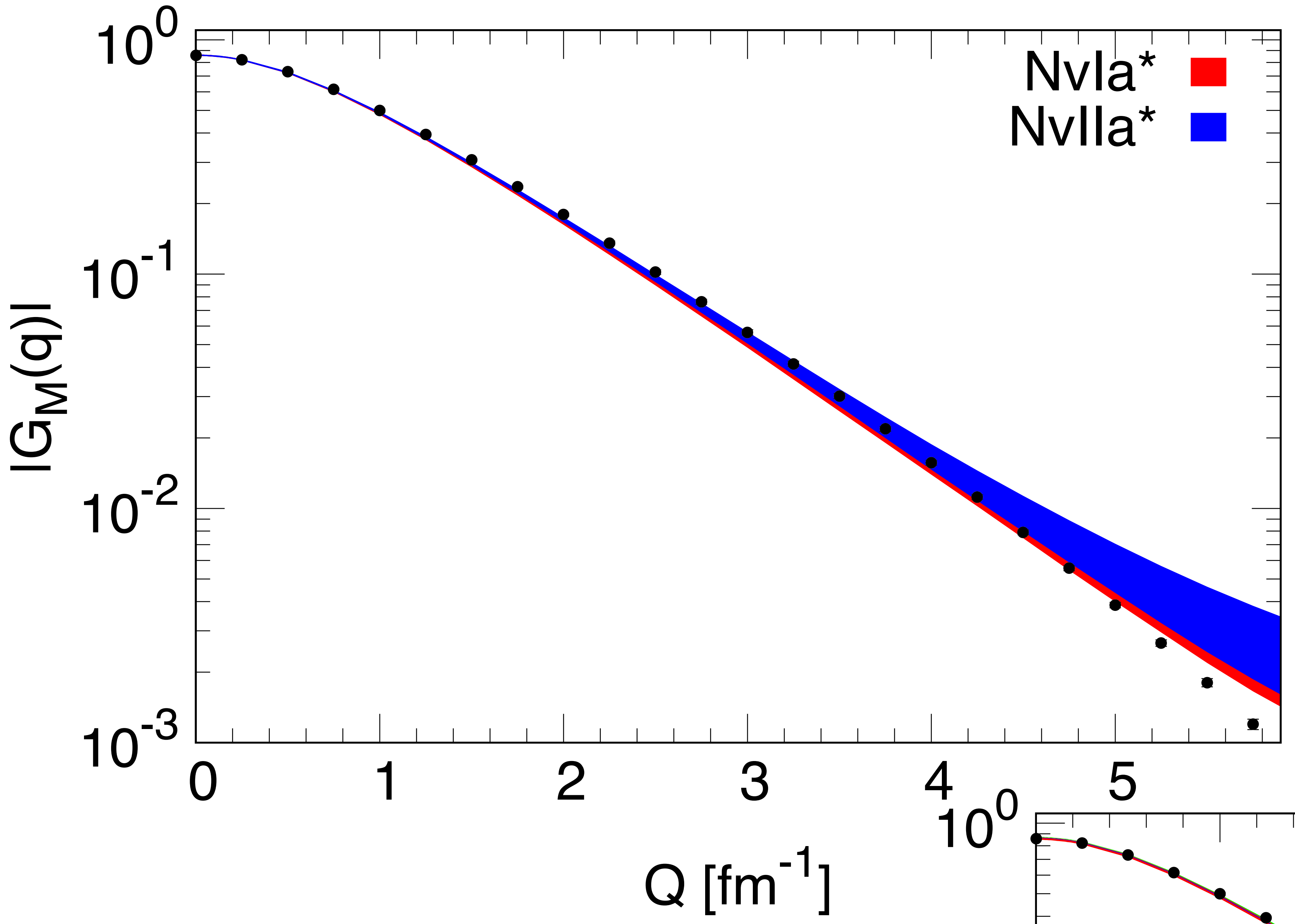


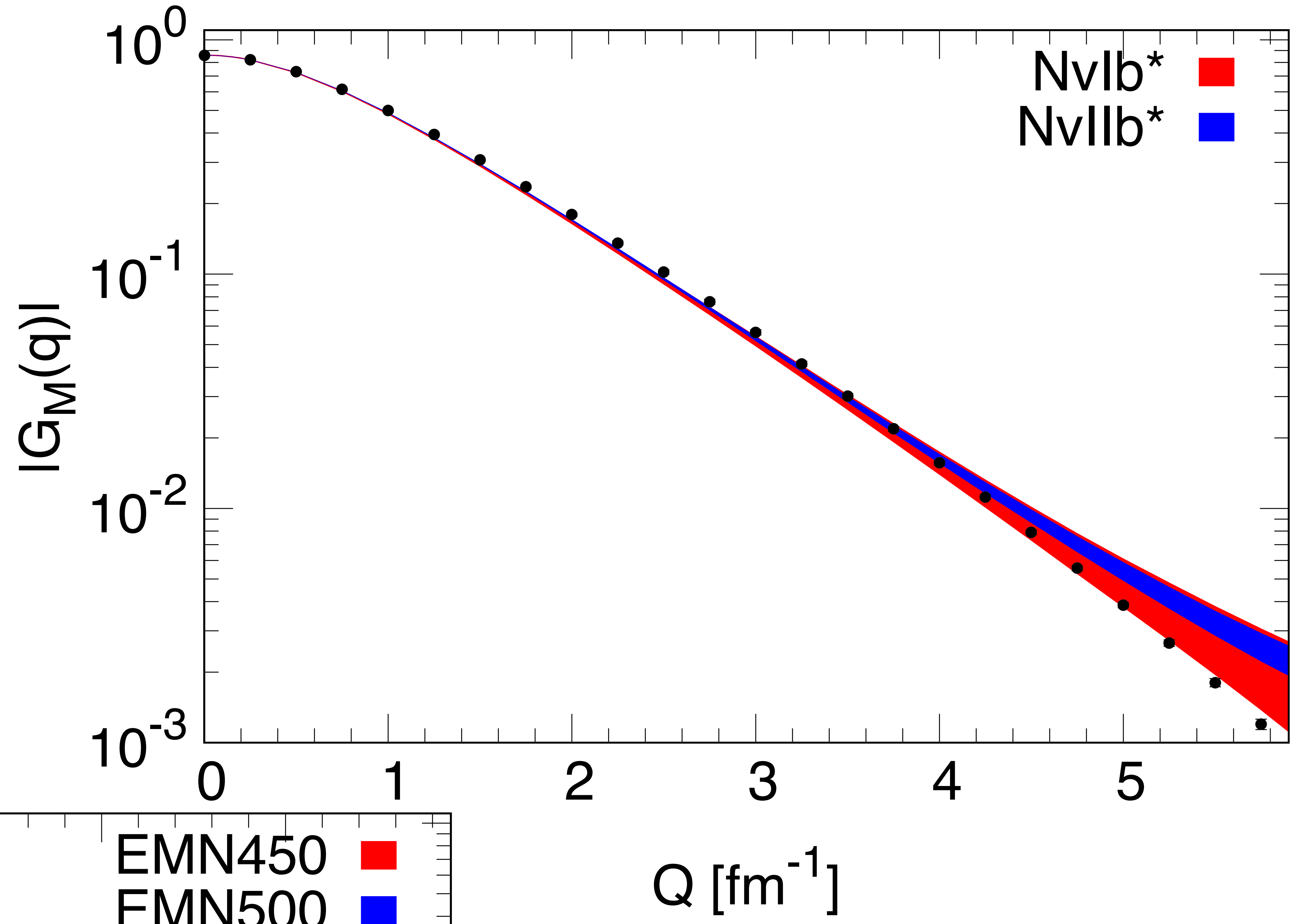
d-threshold

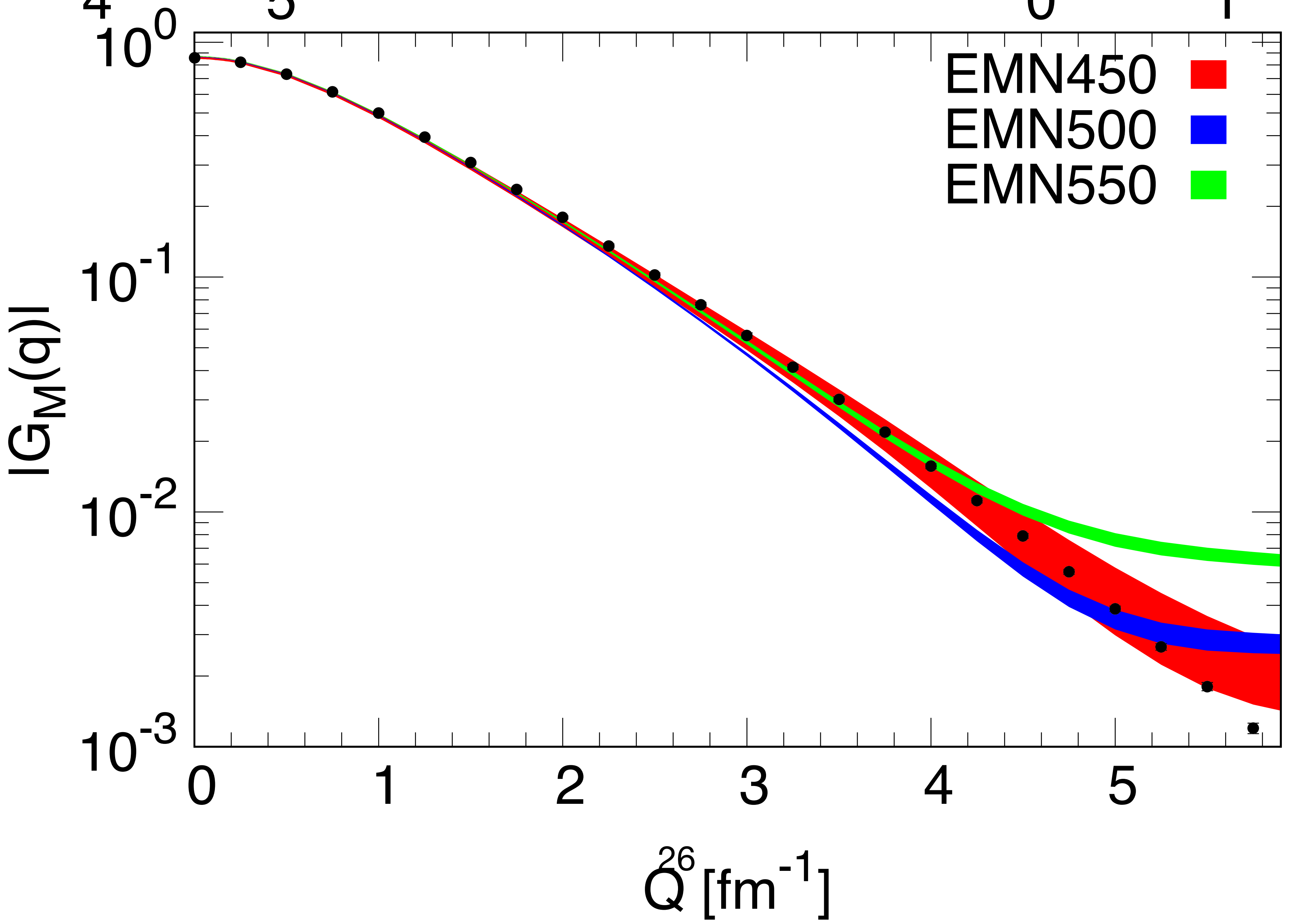


σ(Q²)[fm²/(MeV sr)]
Q² [fm⁻²]
NvIa*
NvIIa*
NvIb*
NvIIb*
EMN450
EMN500
EMN550

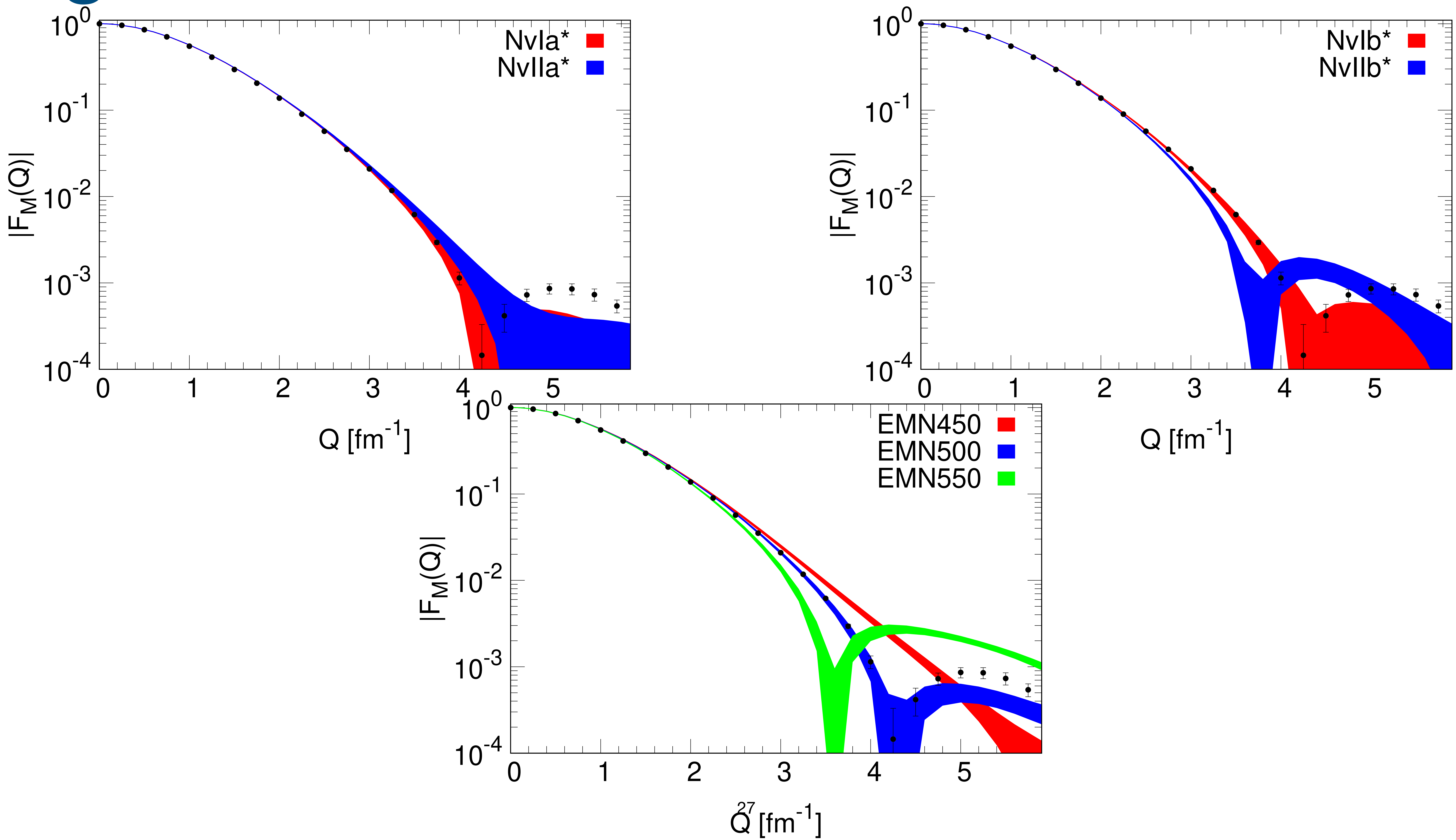
Magnetic form factors of ^{2}H



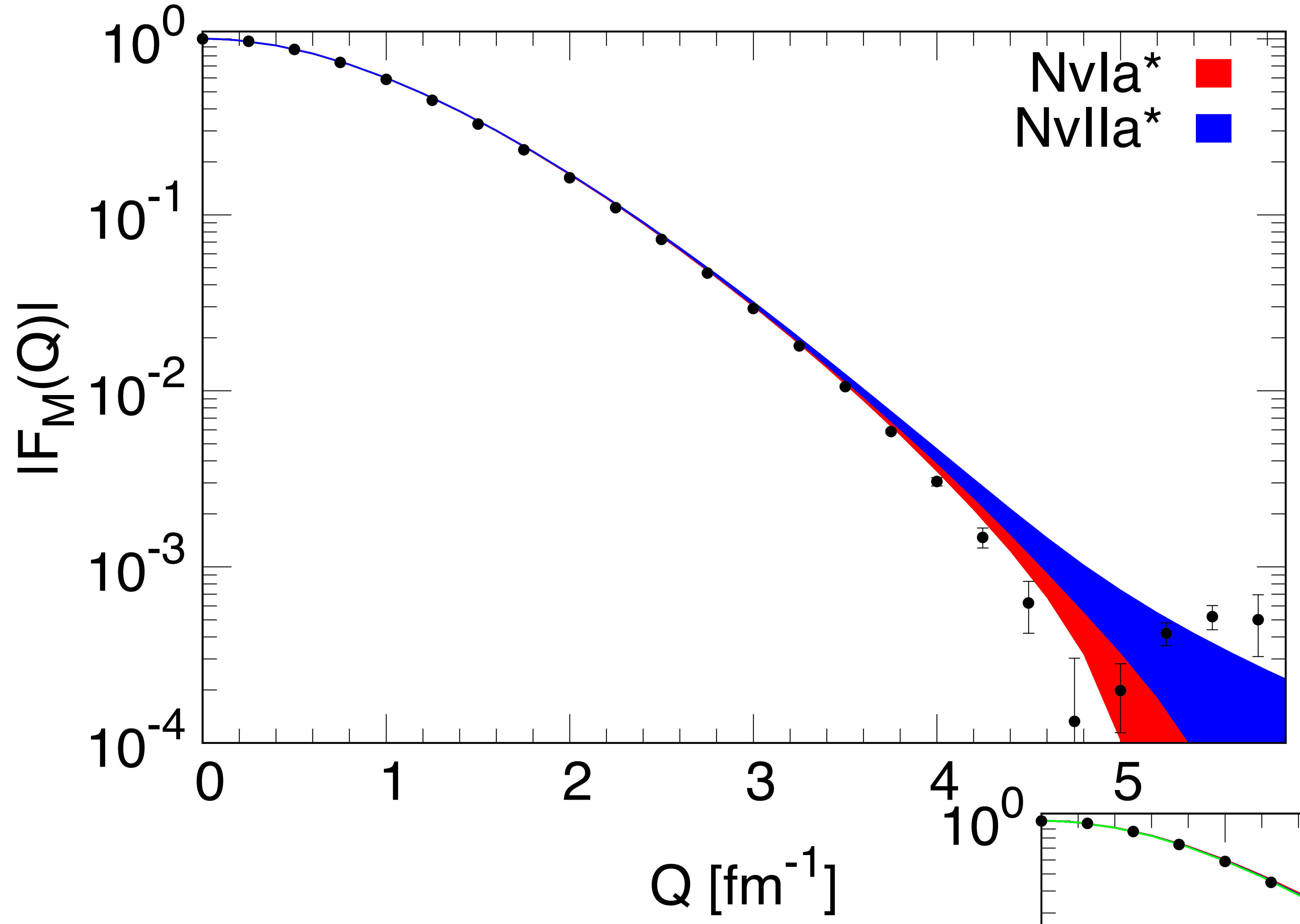


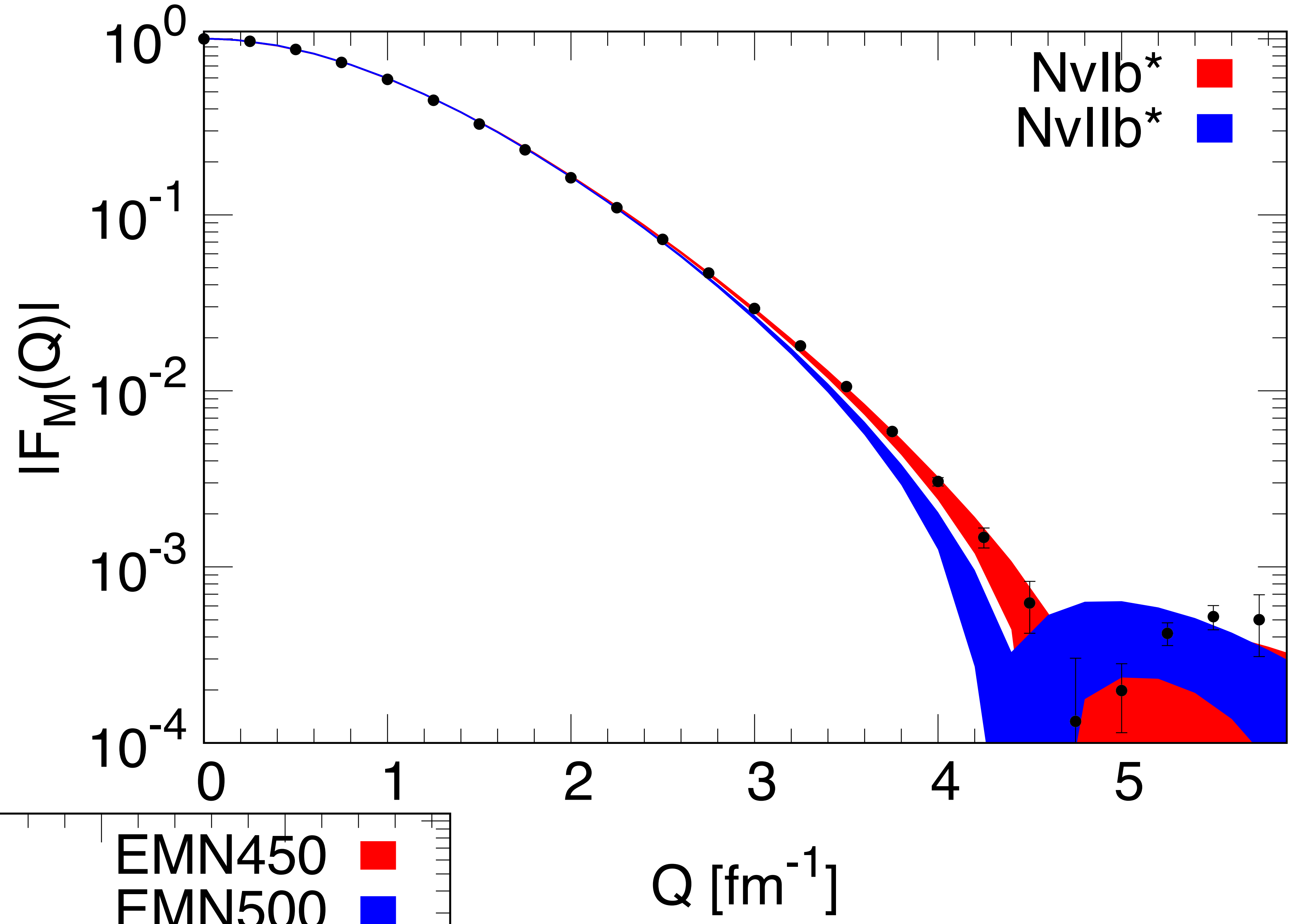


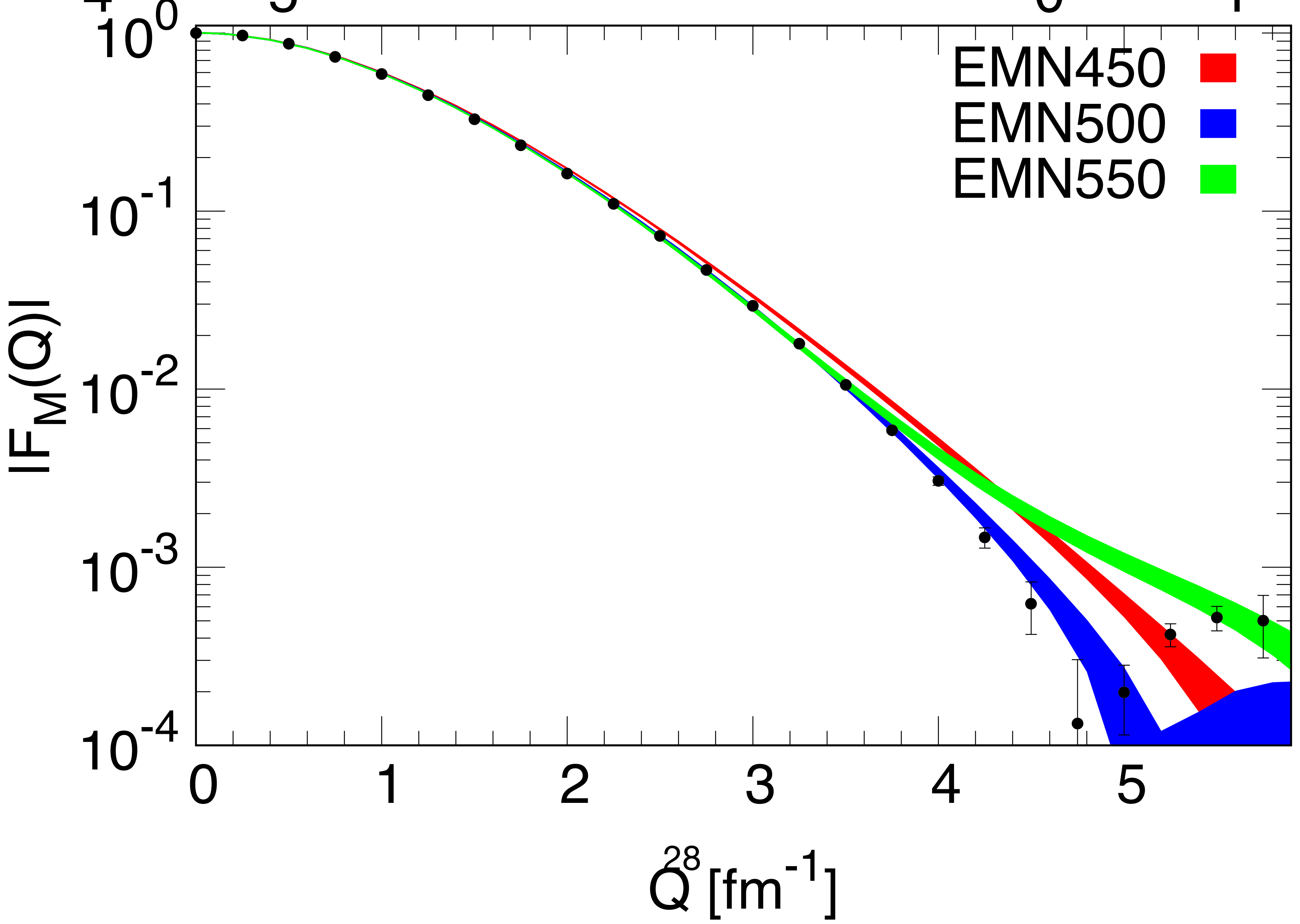
Magnetic form factors of ^{3}He



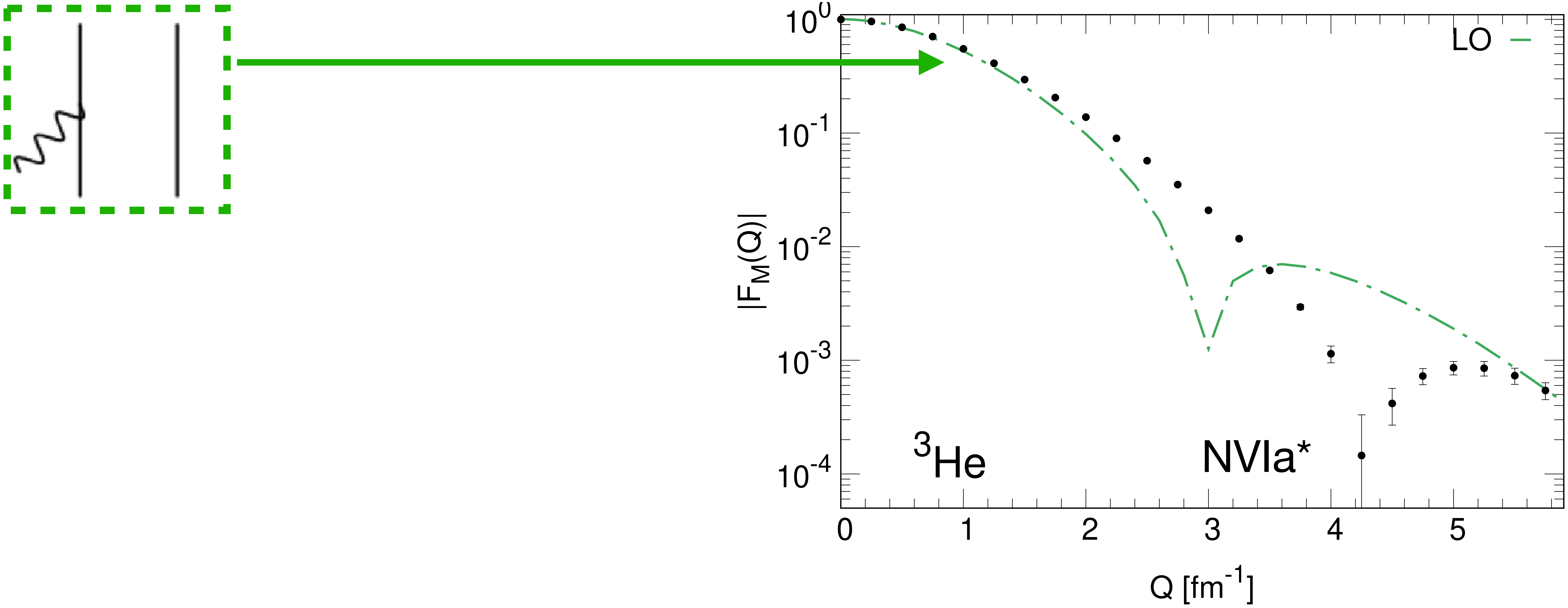
Magnetic form factors of ^{3}H



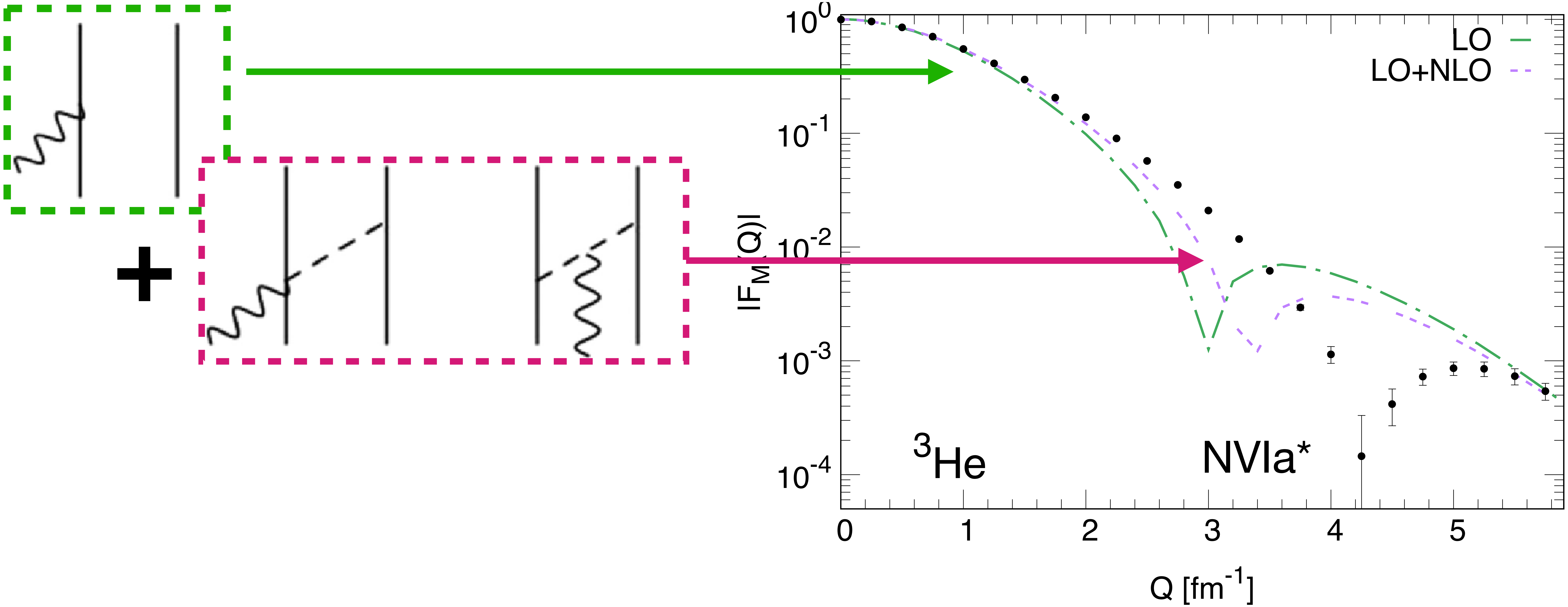




Prediction of A=3 Magnetic Form Factors



Prediction of A=3 Magnetic Form Factor



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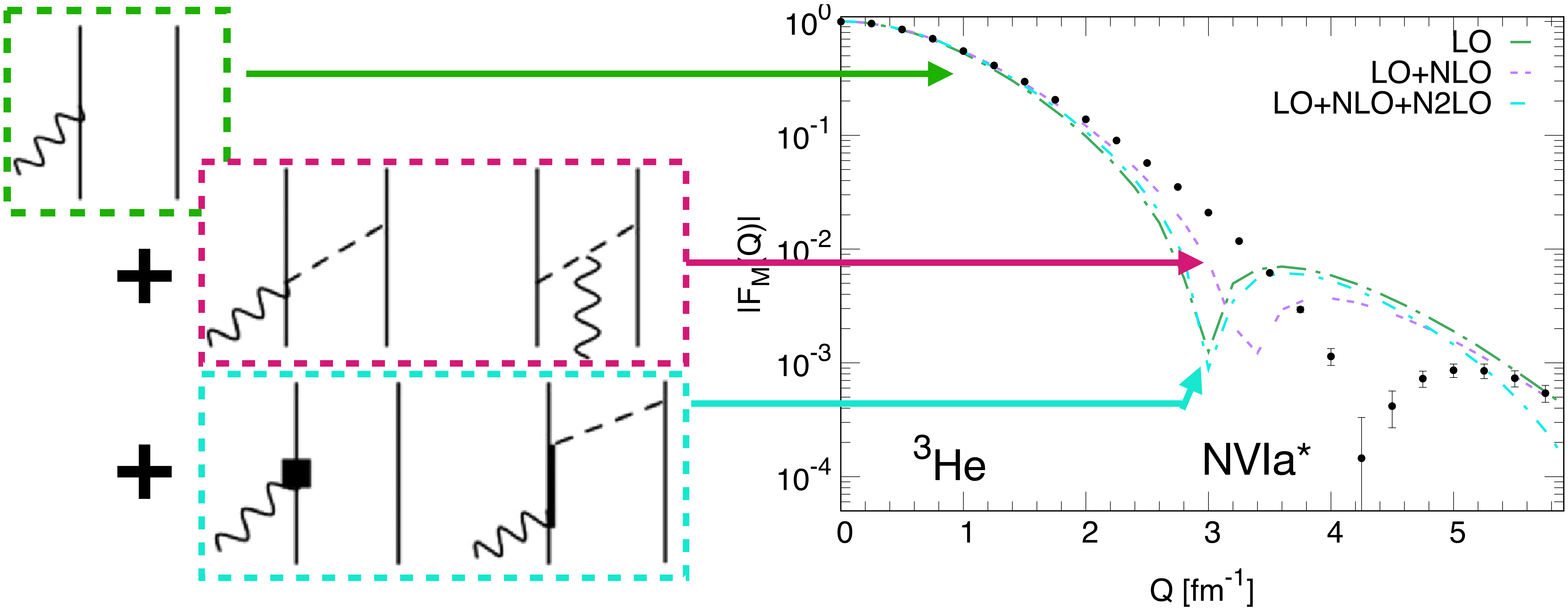

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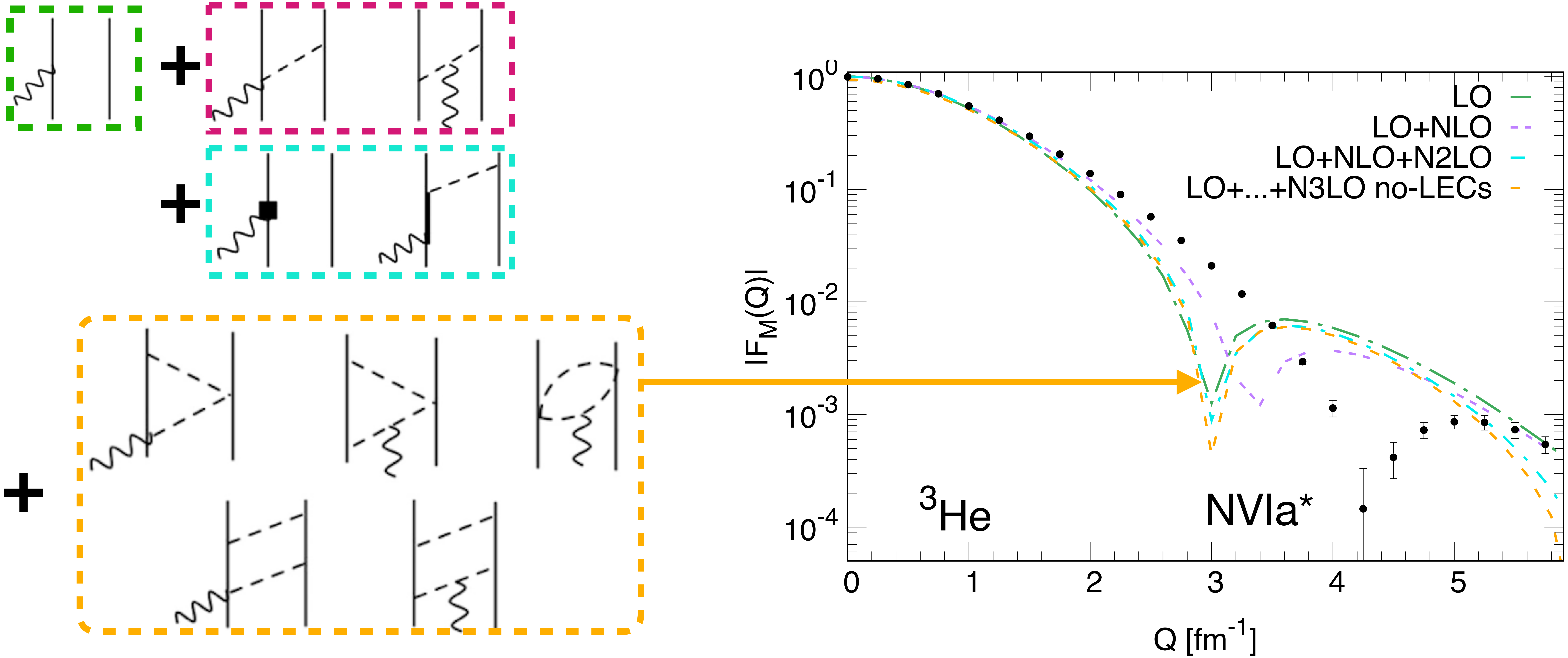

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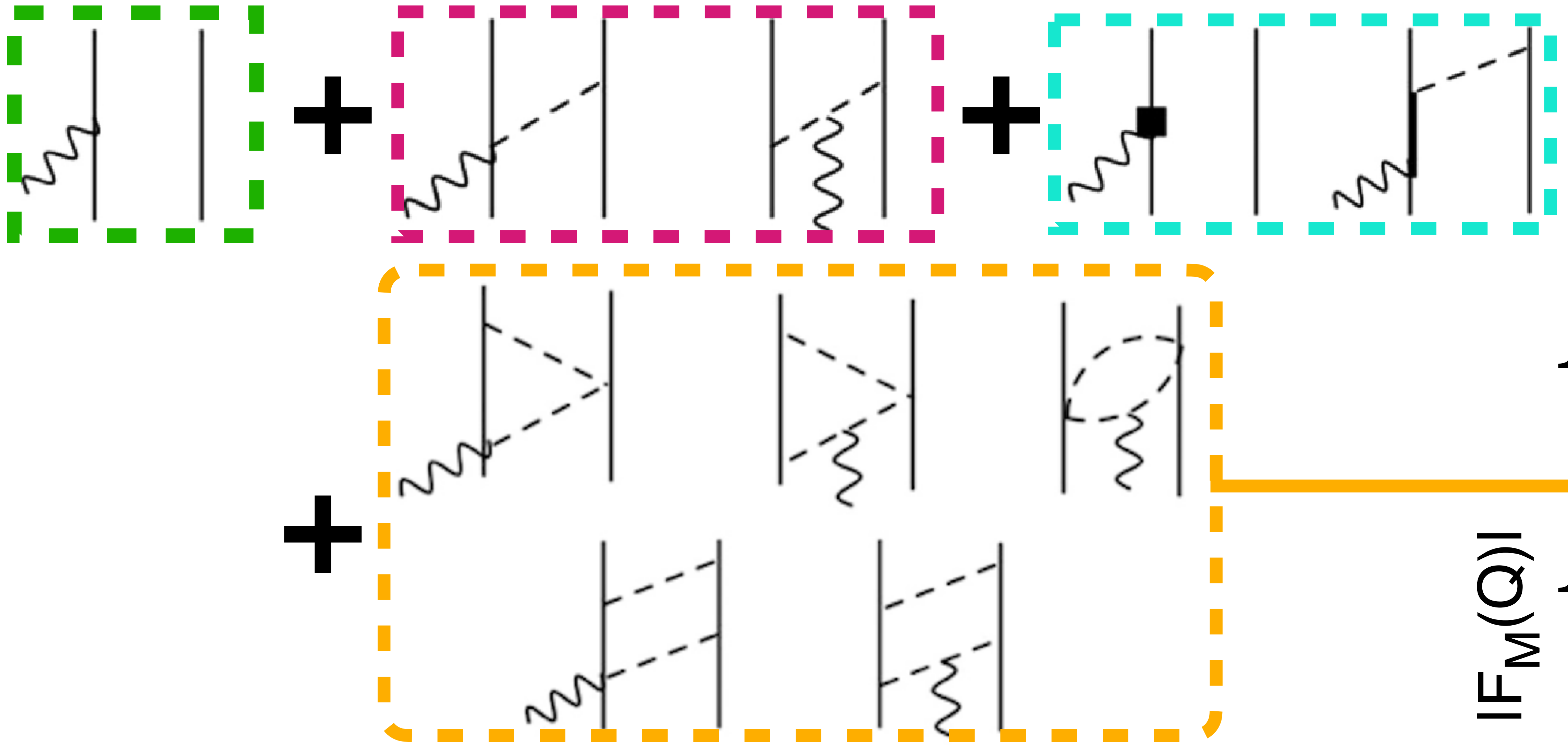
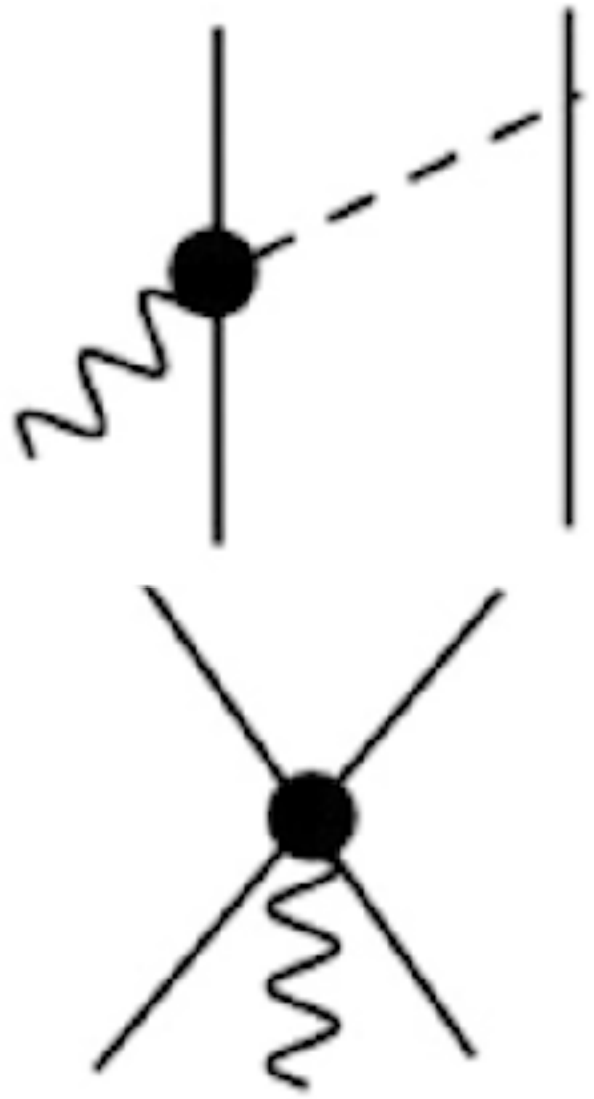
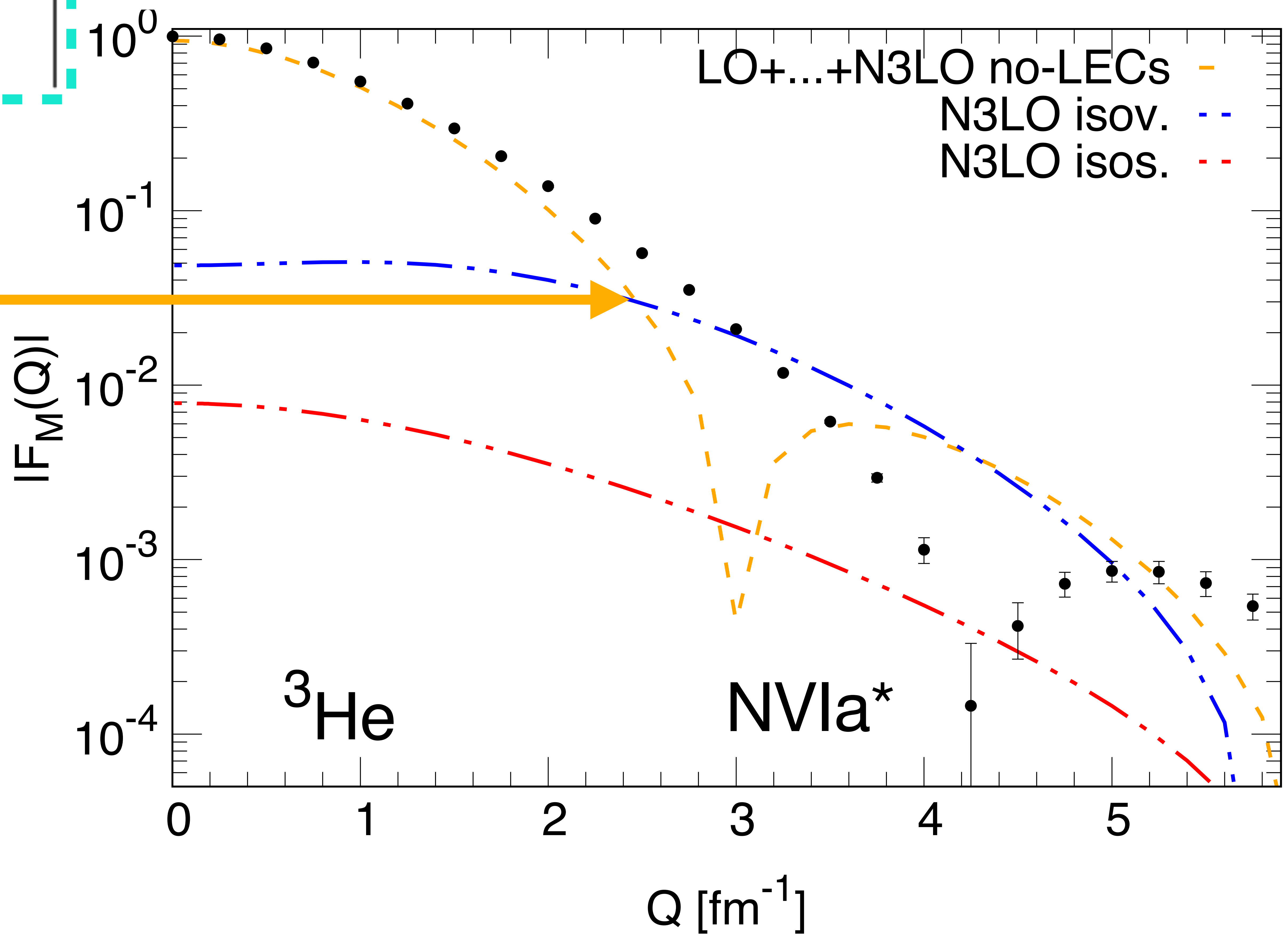




d_2^V d_3^V d_2^S

d_1^V d_1^S



Reliability of the predictions

Is χEFT able to describe large Q?

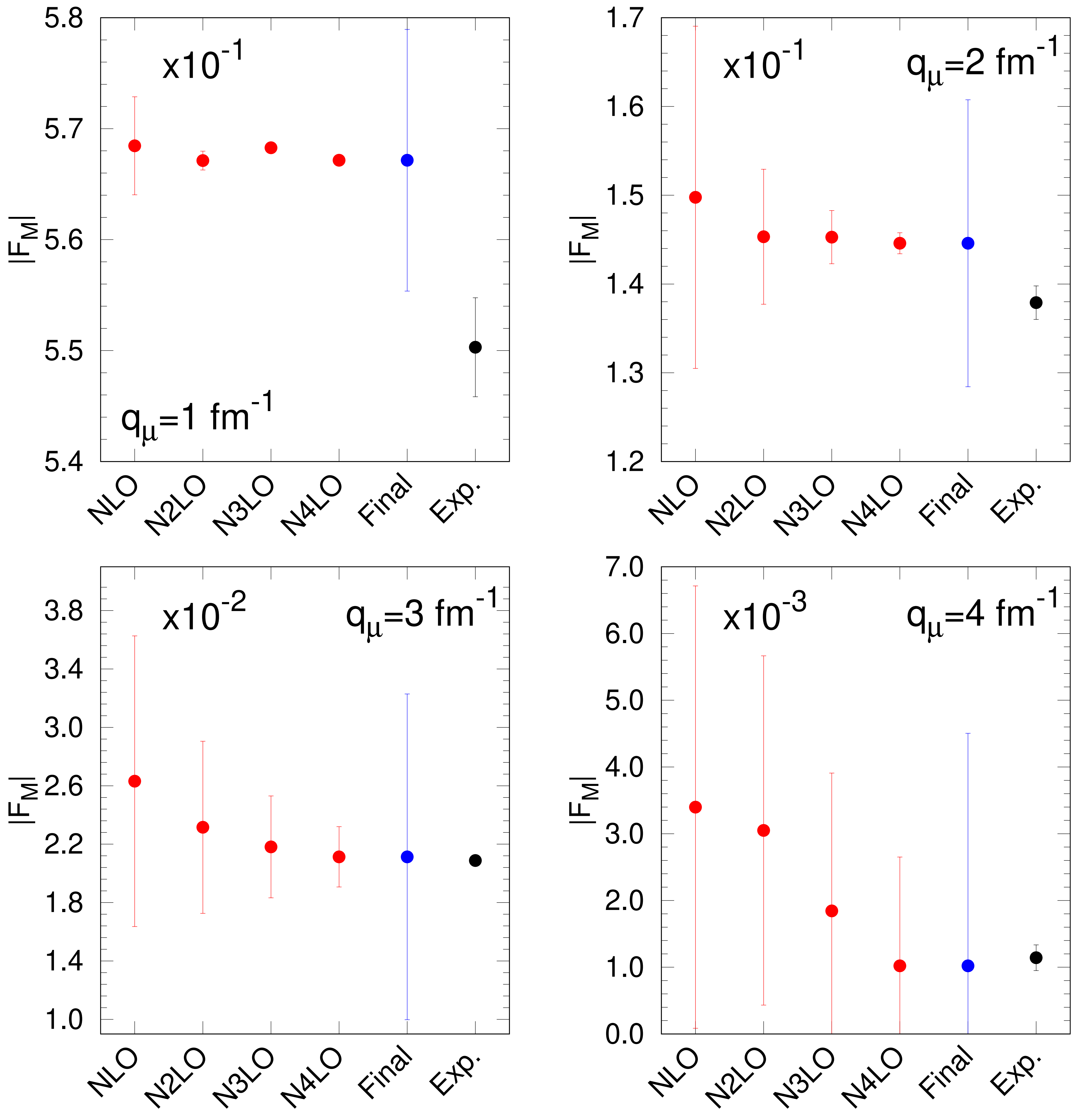
- Truncation errors (as [EPJA 51, 53 (2015)])

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

- Nuclear interaction + currents

- Systematic explodes after

$$Q^2 > 0.5 \text{ GeV}^2$$



^{3}He EMN500

Naive truncation error estimate

Is χEFT able to describe large Q^2?

- 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

- Systematic explodes after

$$Q^2 > 0.5 \text{ GeV}^2$$