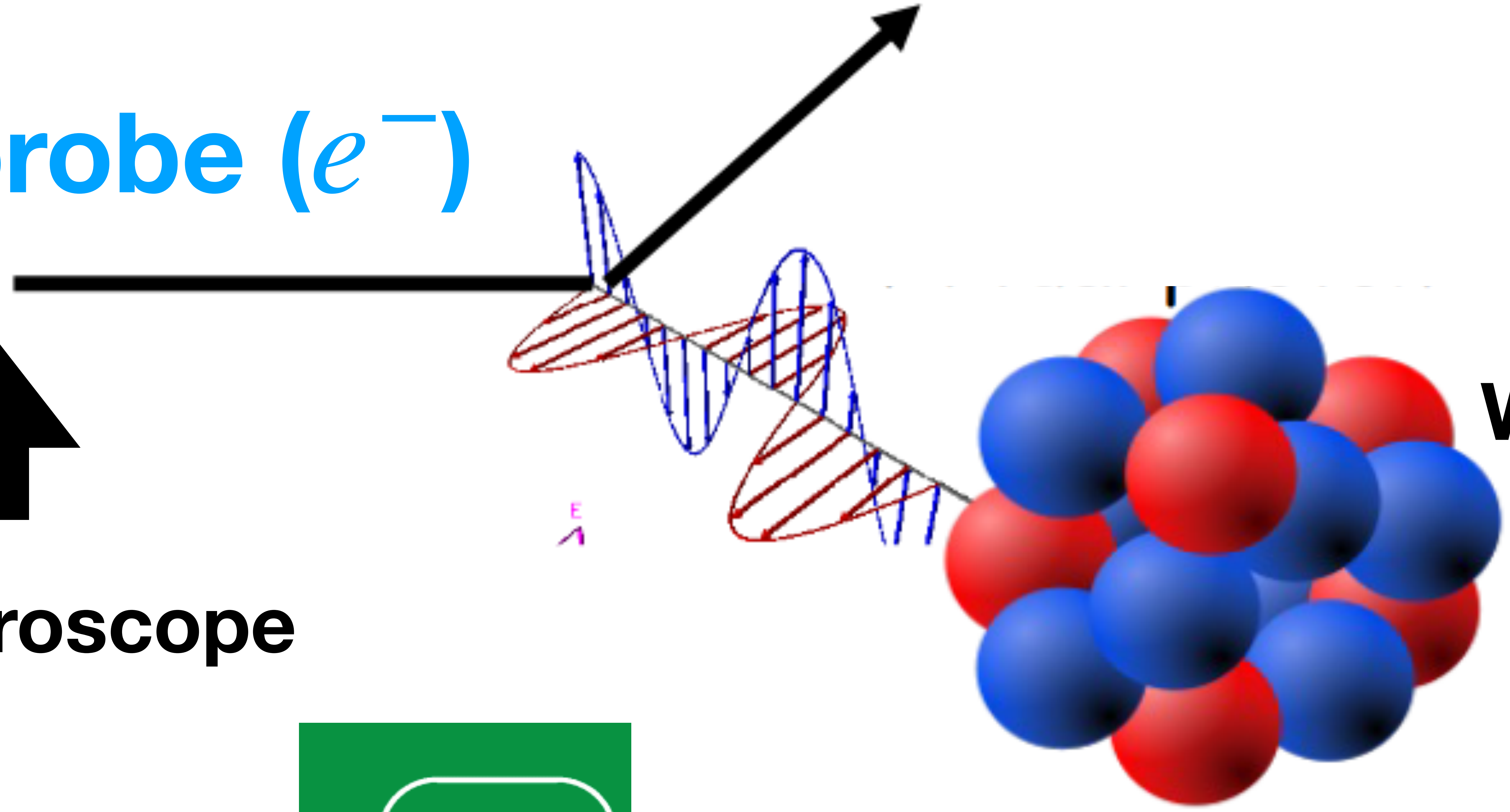
Electro-scattering on nuclei for neutrinos and beyond

Lepton Interactions with Nucleons and Nuclei
Marciana Marina, Isola d'Elba, Italy
June 23-27, 2025

Alex Gnech (agnech@odu.edu)

Studying the nature of the strong interaction

External probe (e^-)



The microscope

What we want to study

Nucleus

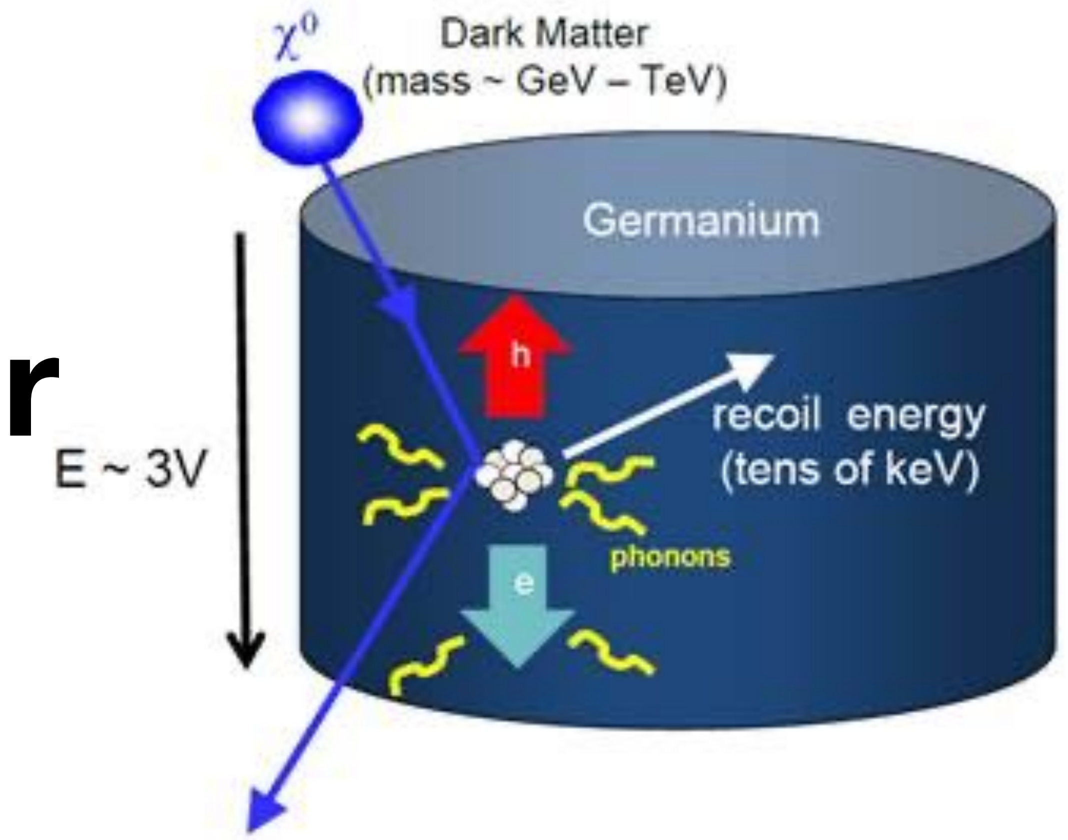
Jefferson Lab

mami
MAINZER MIKROTRON

EIC

Fundamental physics with nuclei

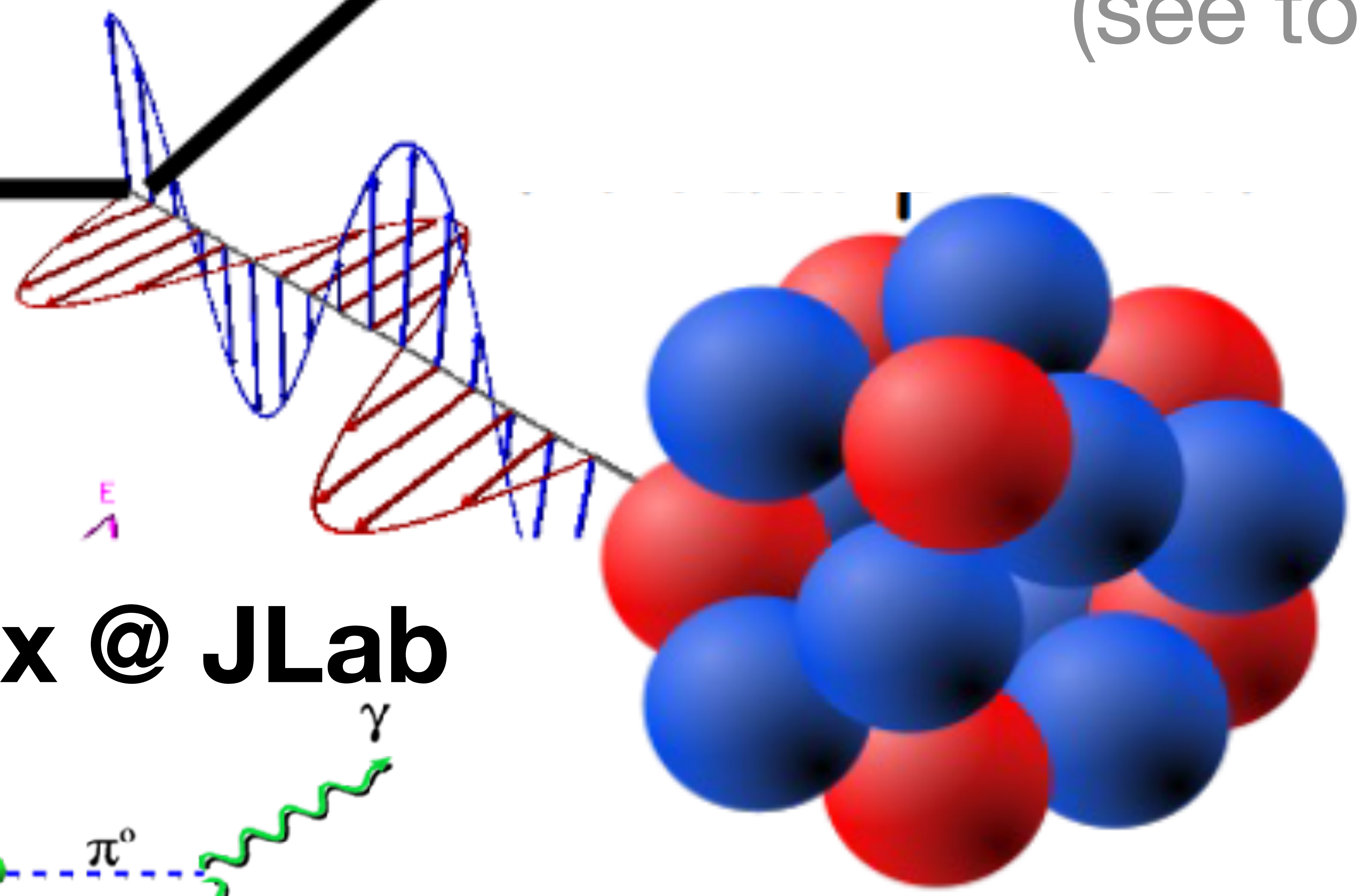
What we want to study



Dark matter

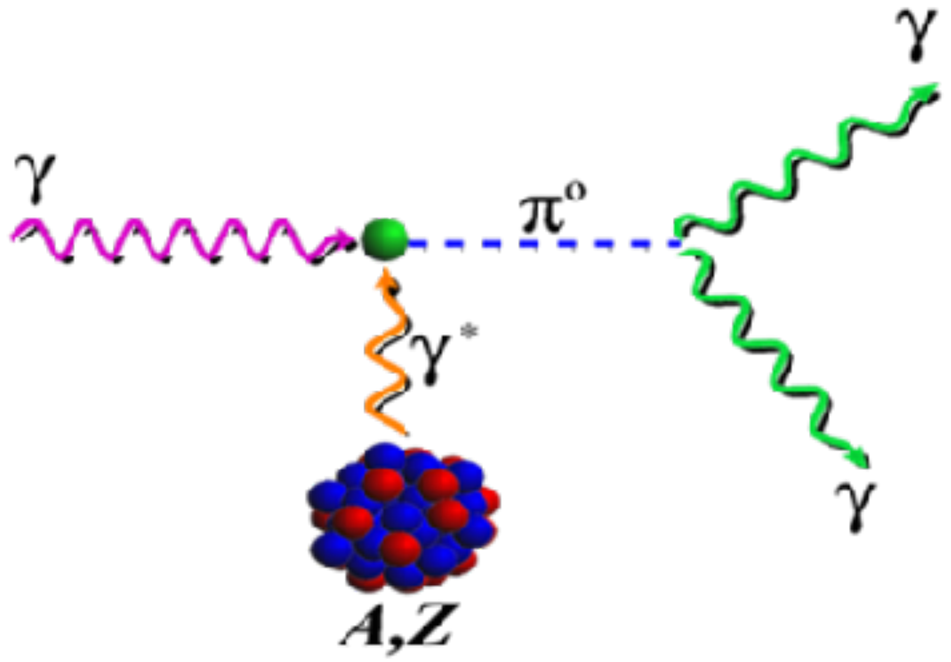
(see tomorrow session)

External probes



Neutrino Physics

PrimEx @ JLab



Nucleus

The microscope

An accurate understanding of nuclear structure and dynamics is needed to extract new physics from nuclear effects

↓

Comprehensive quantitative and predictable theory description of all nuclear structure and reaction

Scattering of electrons on nuclei (elastic)

$$\frac{d\sigma}{d\Omega} = 4\pi\sigma_M f_{\text{rec}}^{-1} \left[\frac{Q^4}{q^4} F_L^2(q) + \left(\frac{Q^2}{2q^2} + \tan^2\theta_e/2 \right) F_T^2(q) \right]$$

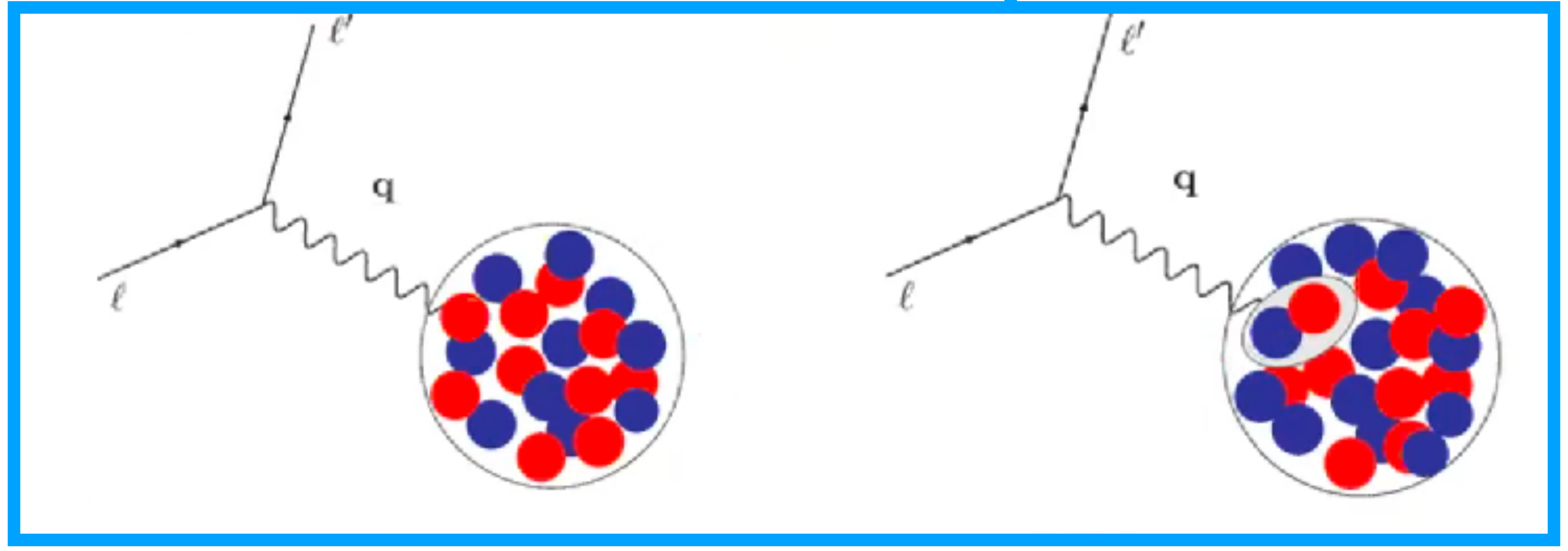
$$F_L(q) \propto \langle \psi | \rho(q) | \psi \rangle$$

$$F_T(q) \propto \langle \psi | j_y(q) | \psi \rangle$$

$$H|\psi\rangle = E|\psi\rangle$$

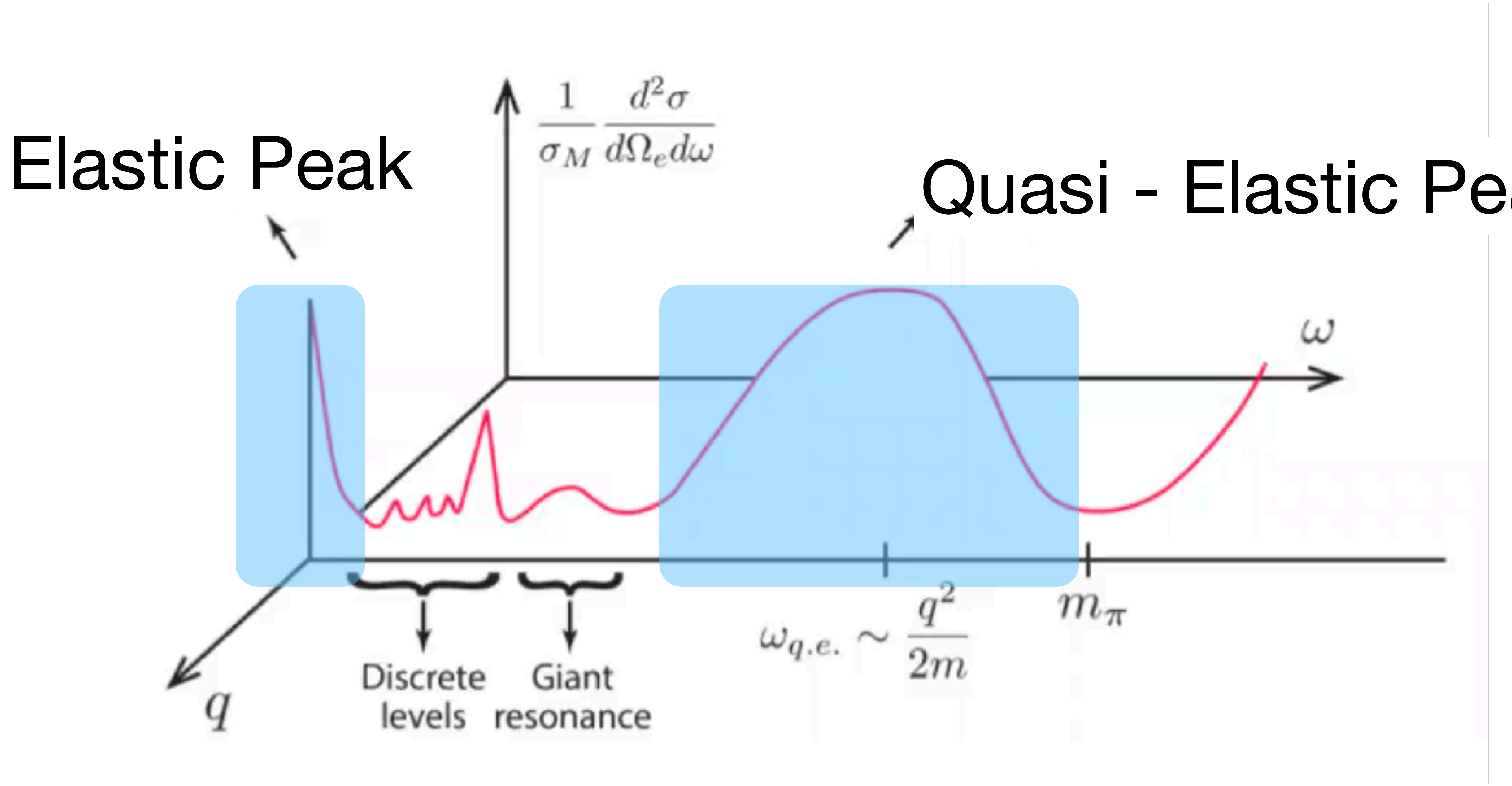
$$H = \sum_i T_i + \sum_{i<j} v_{ij} + \sum_{i<j<k} v_{ijk}$$

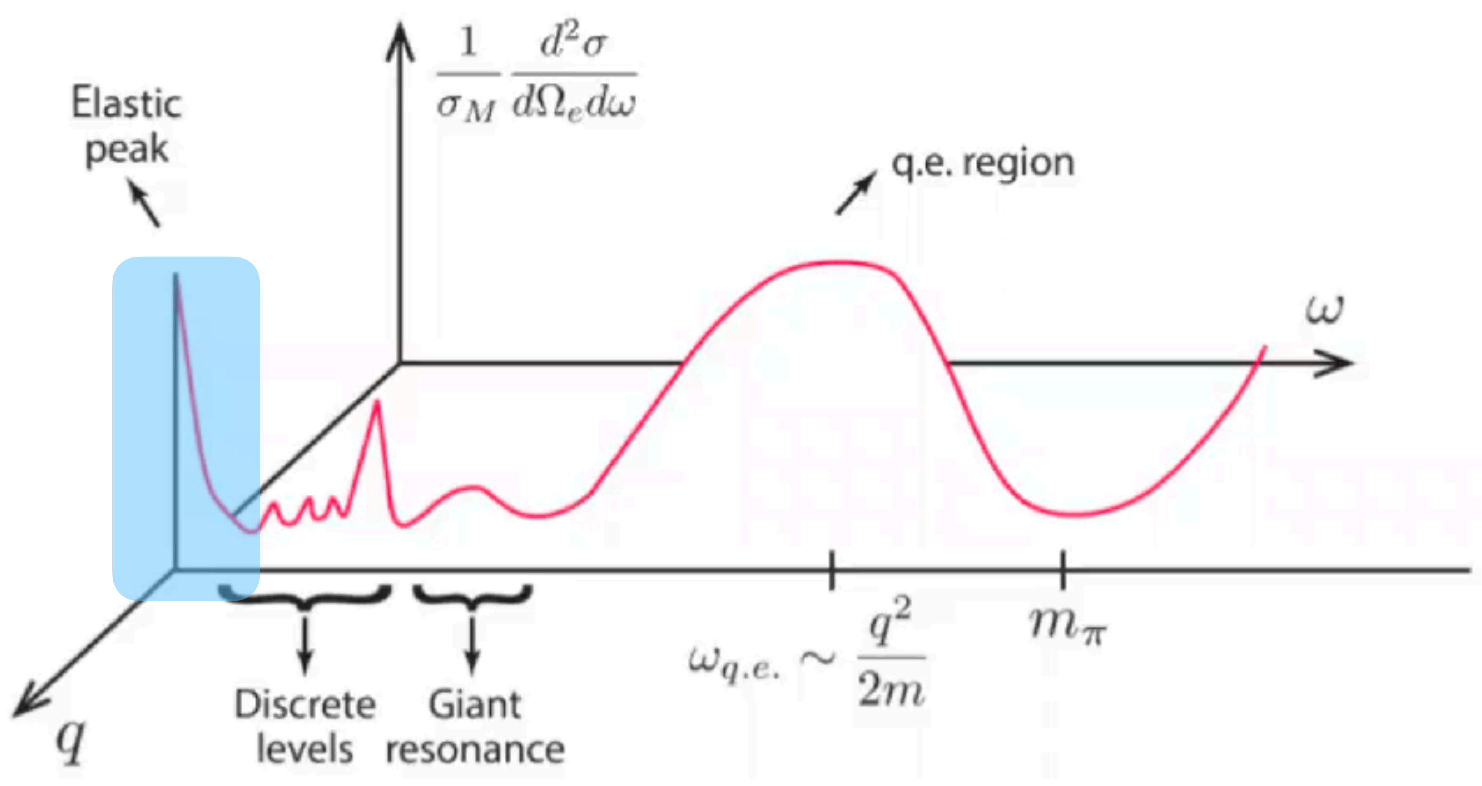
+ Quantum Monte Carlo method (VMC)



Contents

- **Electromagnetic form factors and radii of light nuclei**
- **Response function of light nuclei**
- **Towards inclusion of mesons: Primakoff production**





Electromagnetic form factors and radii of light nuclei

[Within chiral effective field theory
(Norfolk interaction +JLab-Pisa currents)]

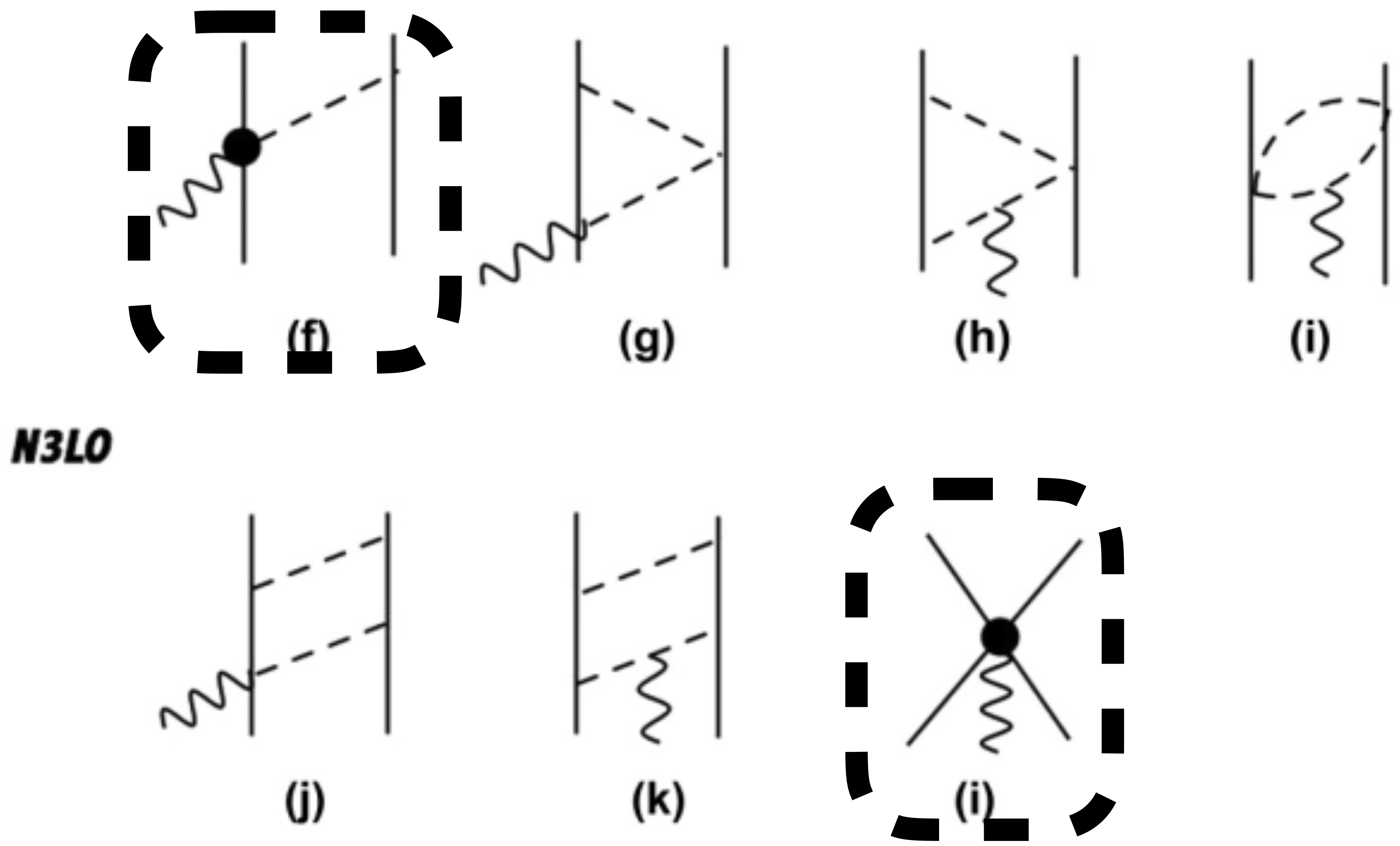
G. Chambers-Wall, G. B. King, S. Pastore, M. Piarulli
A.G., R. Schiavilla, R. B. Wiringa

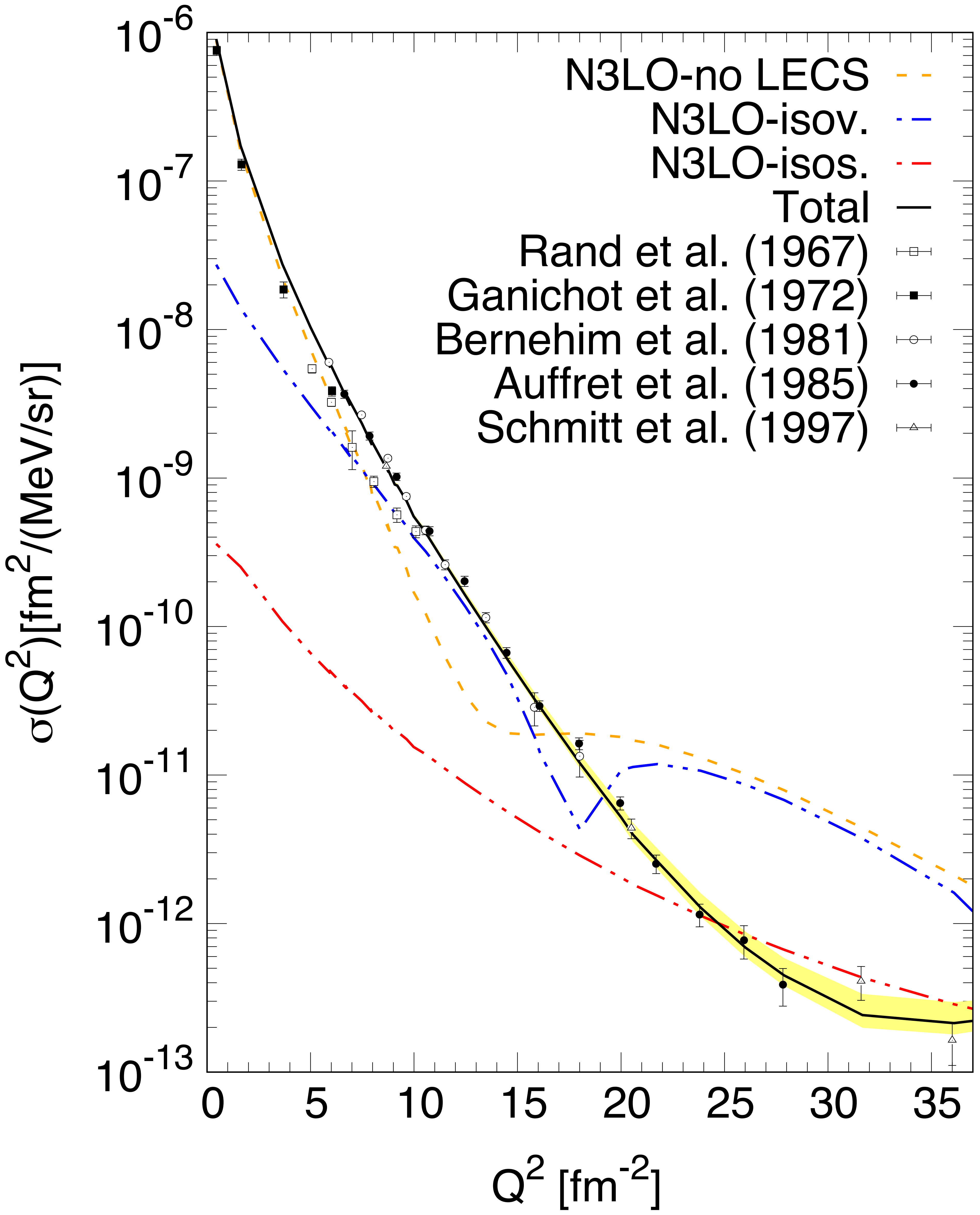
[PRC 106, 04401 (2020), PRL 133, 142501 (2024), PRC 110, 054316 (2024), PRC 110, 054325 (2024), arXiv:2504.04201 (2025)]

New LECs determination

PRC 106, 04401 (2020)

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



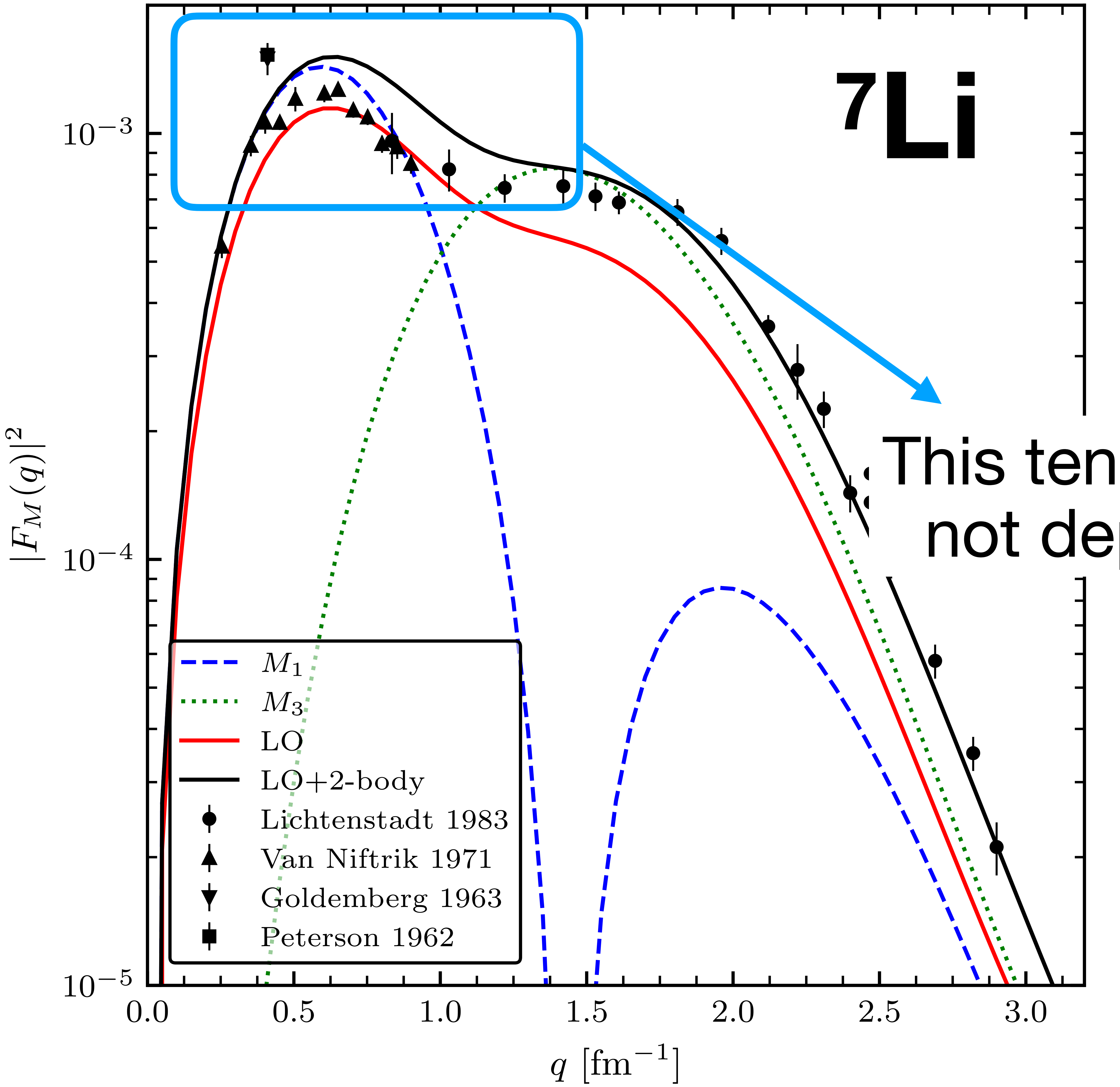


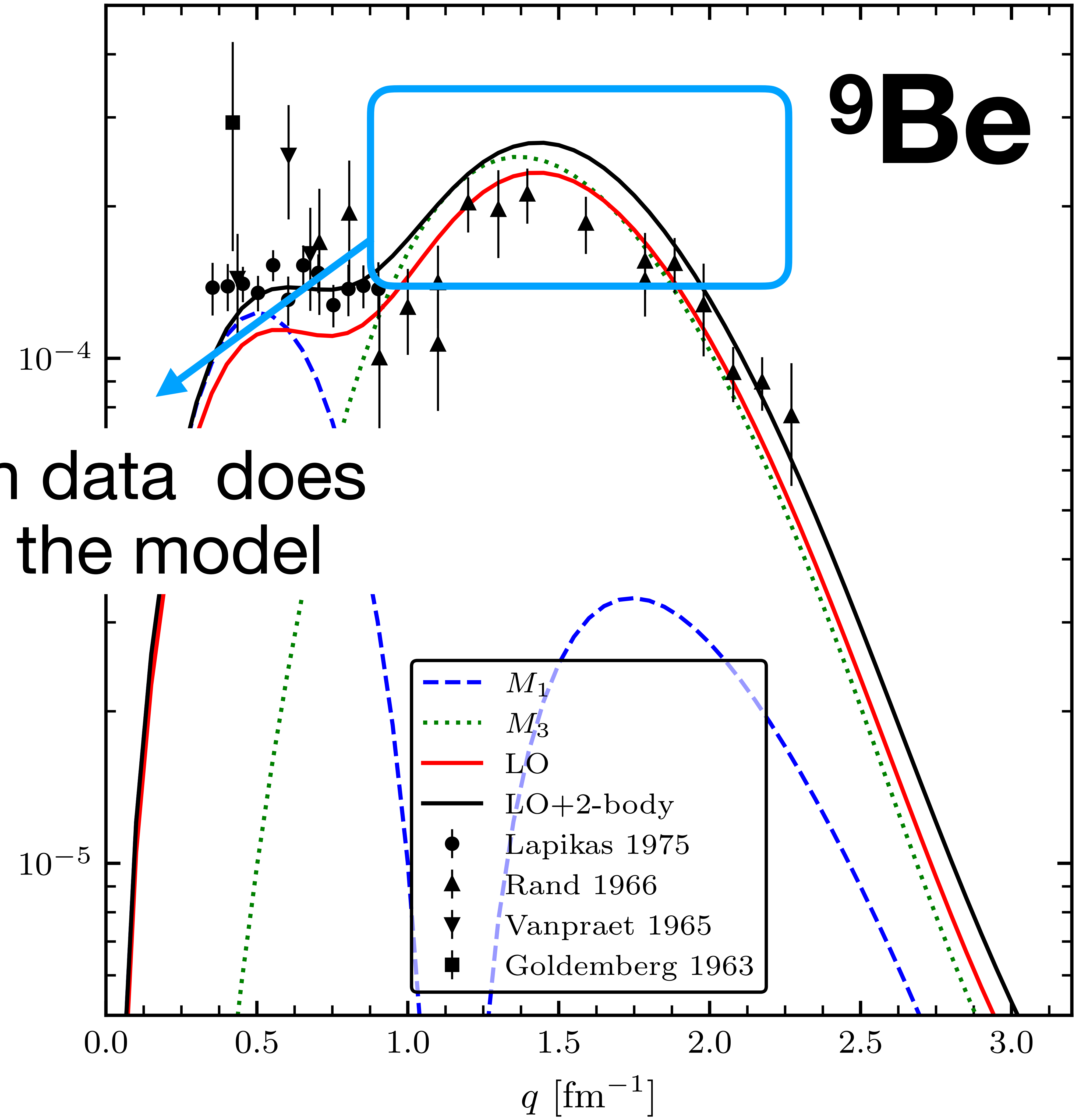
G. Chambers-Wall, et al. PRL 110, 054325 (2024)

Magnetic form factor predictions

Lithium-7 and Berilium-9 (isovector dominated)

NV2-3IIb*



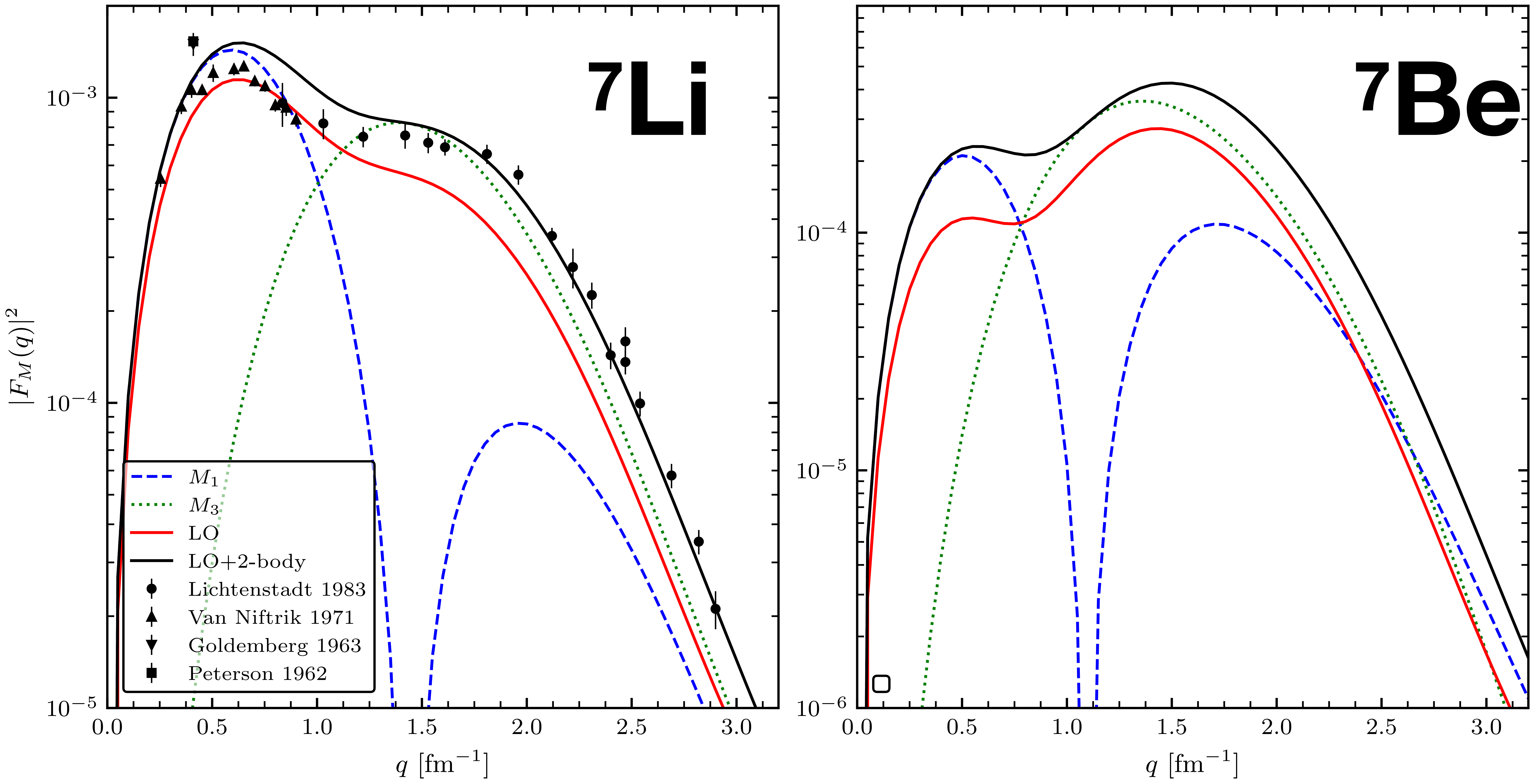


This tension with data does not depend on the model

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 behavior 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

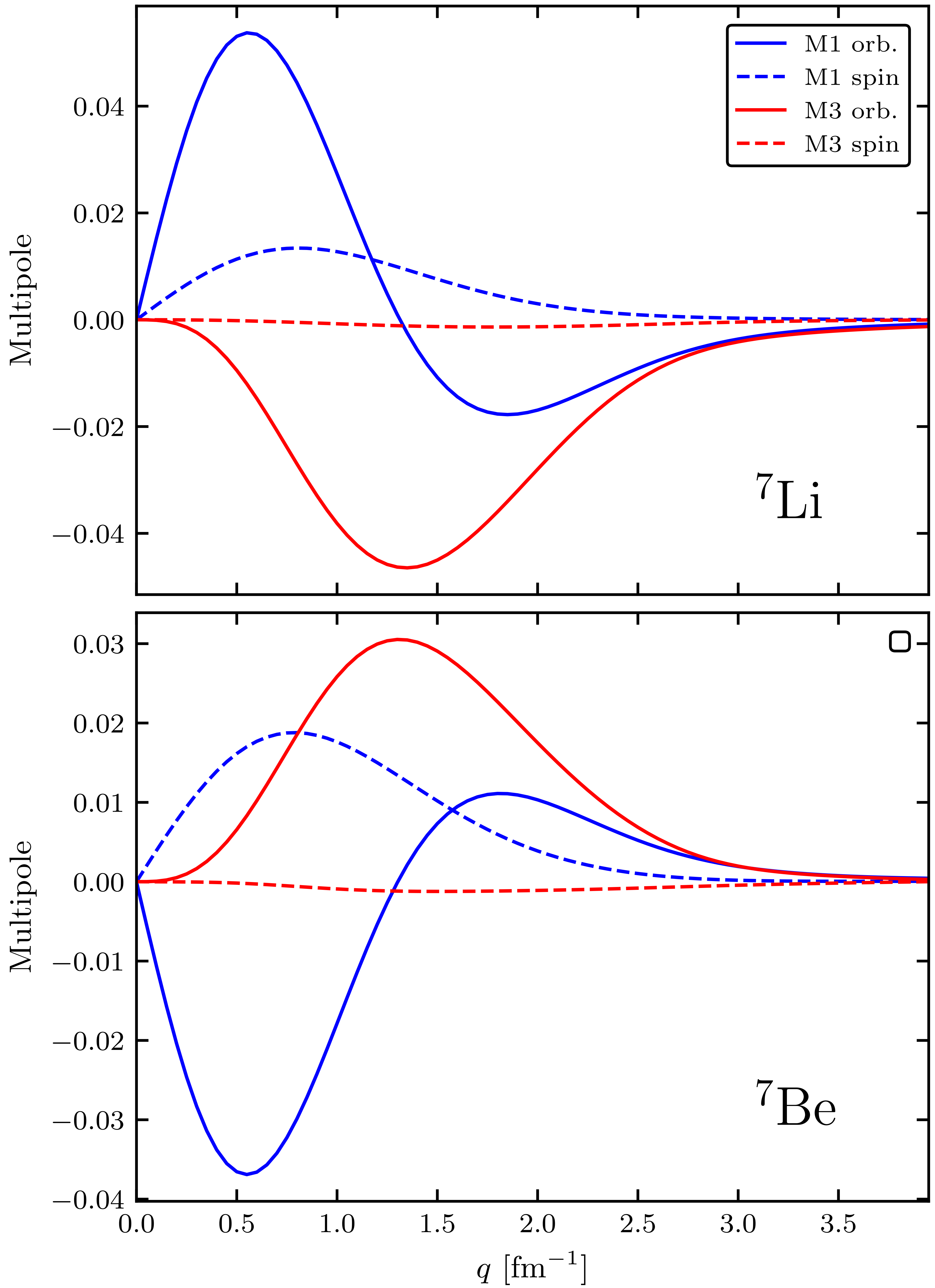
$$\mathbf{j}^{\mathrm{LO}}(\mathbf{q}) = \frac{\epsilon_i(q_\mu^2)}{2\,m}\,\left[\mathbf{p}_i\,,\,\mathrm{e}^{i\mathbf{q}\cdot\mathbf{r}_i}\right]_+ + i\,\frac{\mu_i(q_\mu^2)}{2\,m}\,\mathrm{e}^{i\mathbf{q}\cdot\mathbf{r}_i}\,\sigma_i\times\mathbf{q}\,,$$

Convection current

Magnetic current

No contribution to M_3

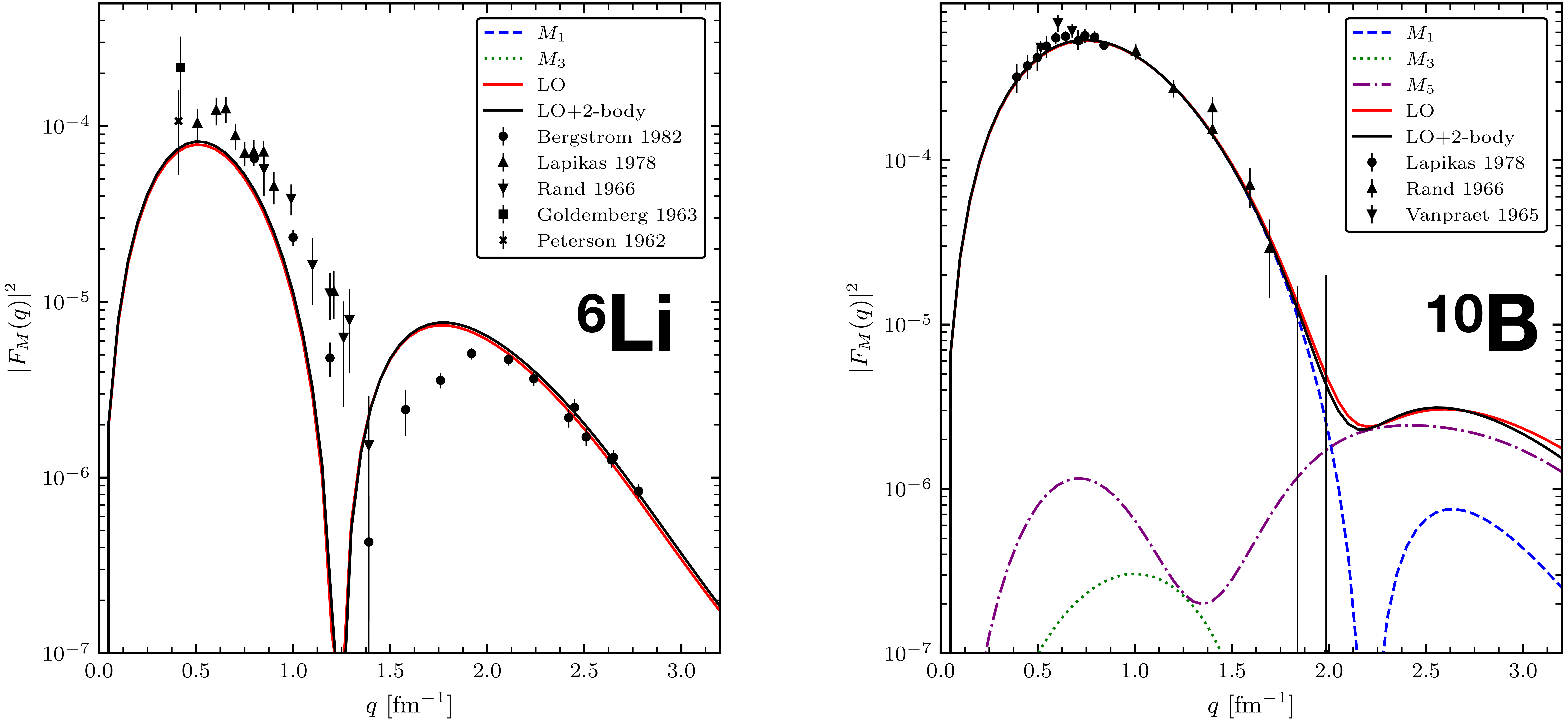
Change sign if there is an unpaired neutron/proton



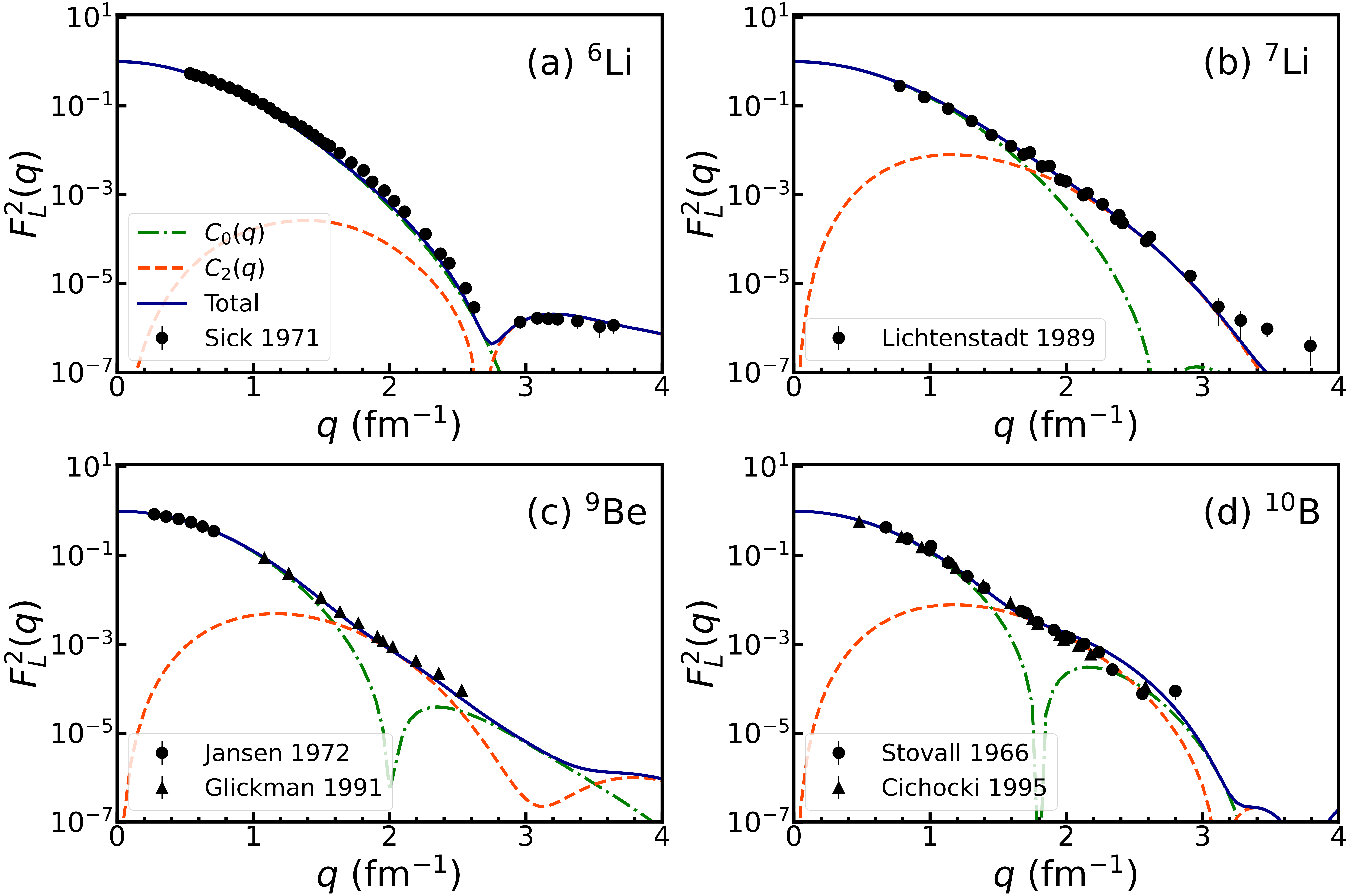
Magnetic form factor predictions

Lithium-6 and Boron-10 (isoscalar transition)

NV2-3IIb*



Charge form factors

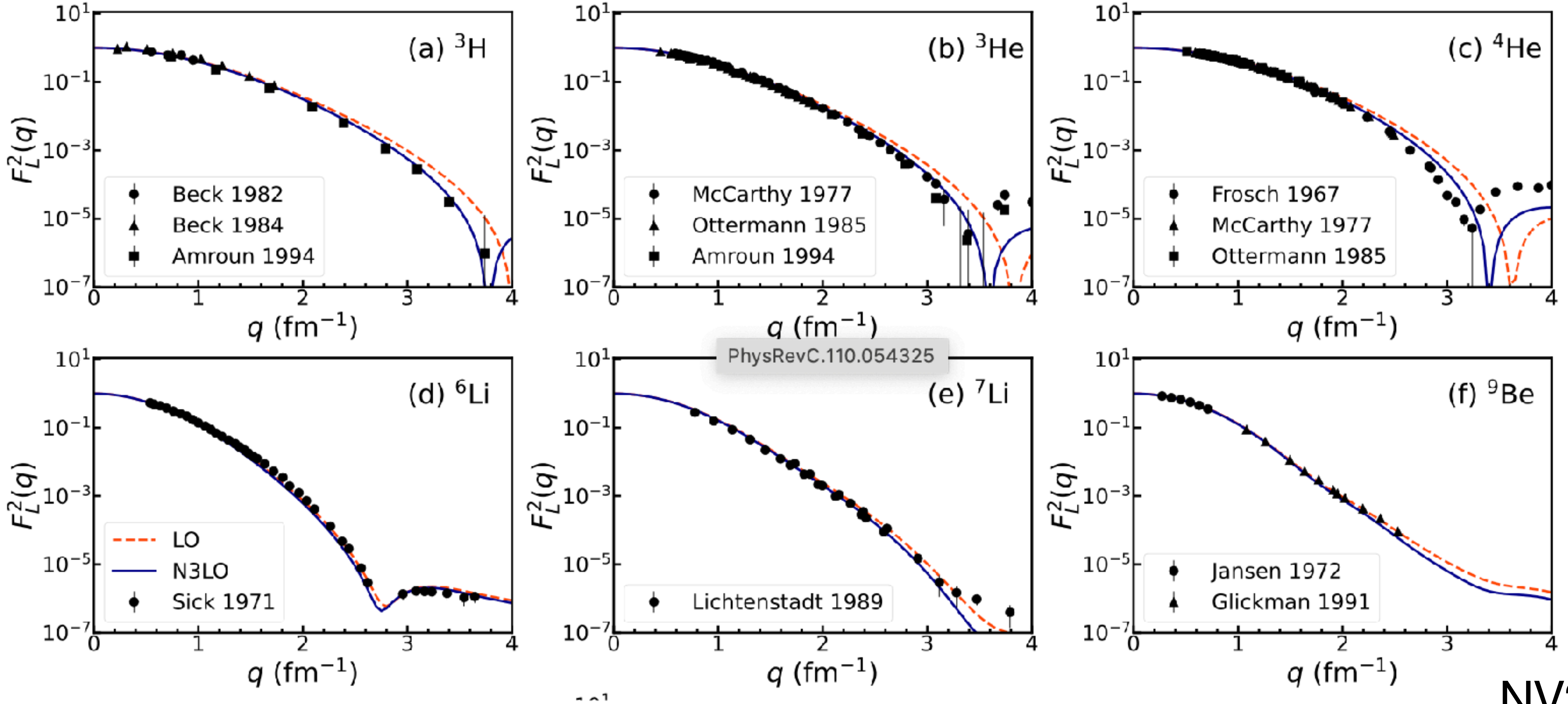


NV2-3IIb*

G.B. King, et al. PRC 110, 054325 (2024)

Charge form factors

Order by order contribution



NV2-3IIb*

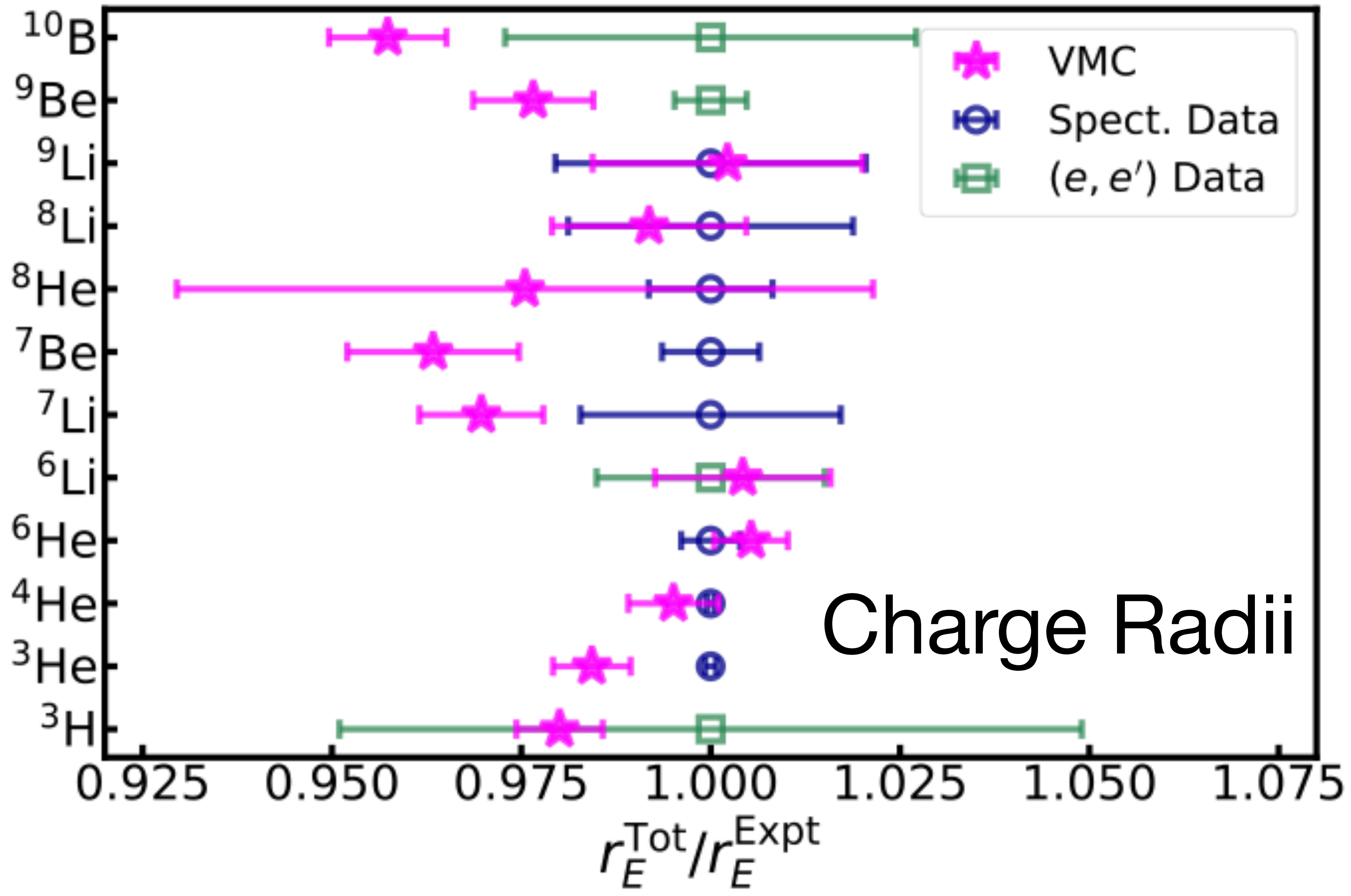
Charge and Magnetic Radii

Derived directly from the form factor extrapolating at $q \to 0$

$$\frac{1}{Z}\langle JJ|\rho(q\hat{\mathbf{z}})|JJ\rangle \approx 1 - \frac{1}{6}r_E^2 q^2 + \mathcal{O}(q^4)\,,$$

	r_M^{LO} (fm)	r_M^{Tot} (fm)	Expt (fm)
$^3\mathrm{H}(\frac{1}{2}^+;\frac{1}{2})$	1.88(2)	1.82(1)	1.840(181) [45]
$^3\mathrm{He}(\frac{1}{2}^+;\frac{1}{2})$	2.02(3)	1.92(2)	1.965(153) [45]
$^6\mathrm{Li}(1^+;0)$	3.32(10)	3.32(10)	–
$^7\mathrm{Li}(\frac{3}{2}^-;\frac{1}{2})$	2.89(7)	2.99(29)	–
$^7\mathrm{Be}(\frac{3}{2}^-;\frac{1}{2})$	3.42(11)	3.37(31)	–
$^8\mathrm{Li}(2^+;1)$	2.22(2)	2.31(1)	–
$^8\mathrm{B}(2^+;1)$	3.04(4)	3.25(2)	–
$^9\mathrm{Li}(\frac{3}{2}^-;\frac{3}{2})$	2.80(7)	2.87(31)	–
$^9\mathrm{Be}(\frac{3}{2}^-;\frac{1}{2})$	3.34(7)	3.28(7)	–
$^9\mathrm{B}(\frac{3}{2}^-;\frac{1}{2})^\dagger$	2.80(9)	2.82(12)	–
$^9\mathrm{C}(\frac{3}{2}^-;\frac{3}{2})^\dagger$	3.34(7)	3.14(30)	–
$^{10}\mathrm{B}(3^+;0)$	2.33(2)	2.33(2)	–

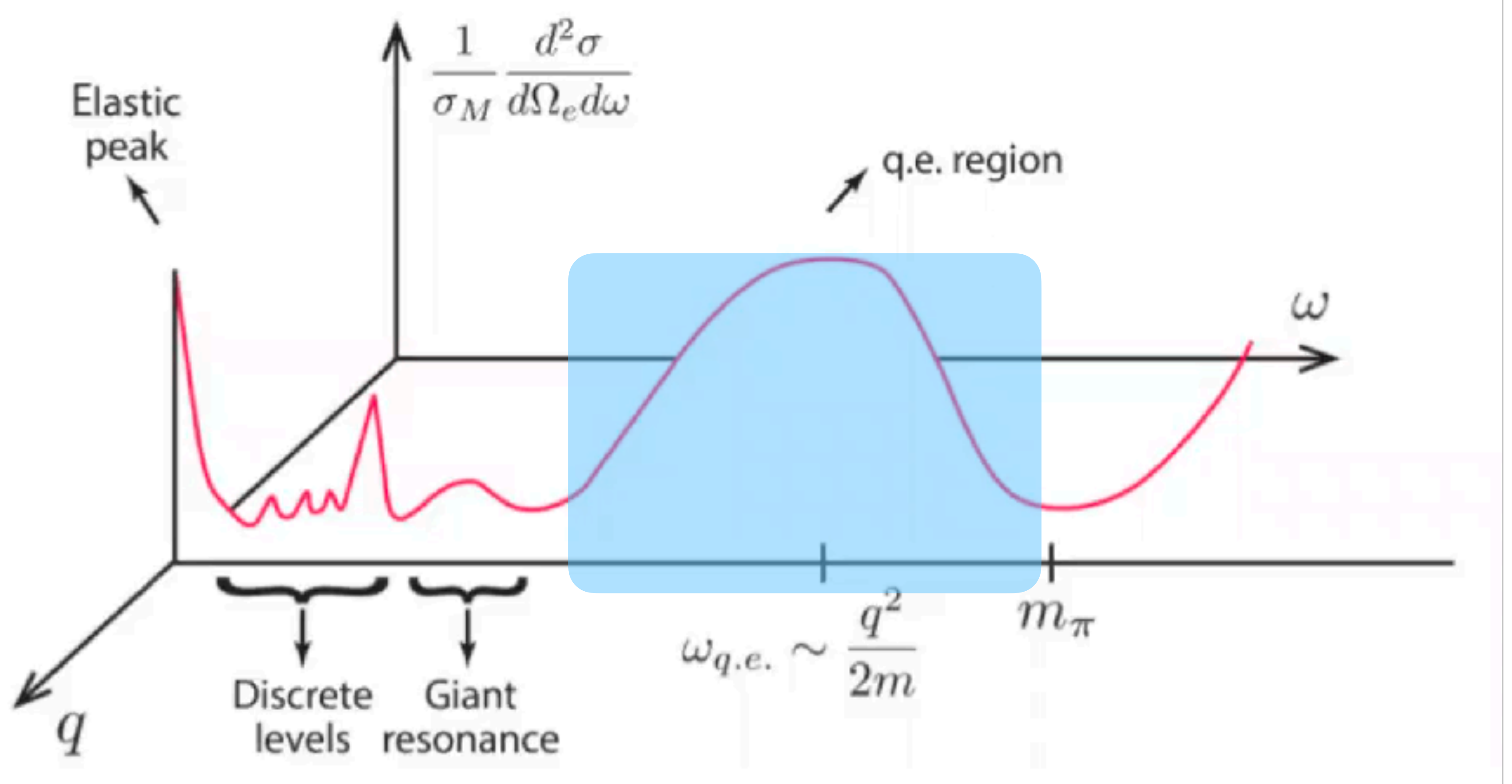
Magnetic Radii



Charge Radii

Automatically take care of the two-body contributions in the currents

see A. Filin talk on Friday



Electromagnetic response function of light nuclei: relativistic corrections

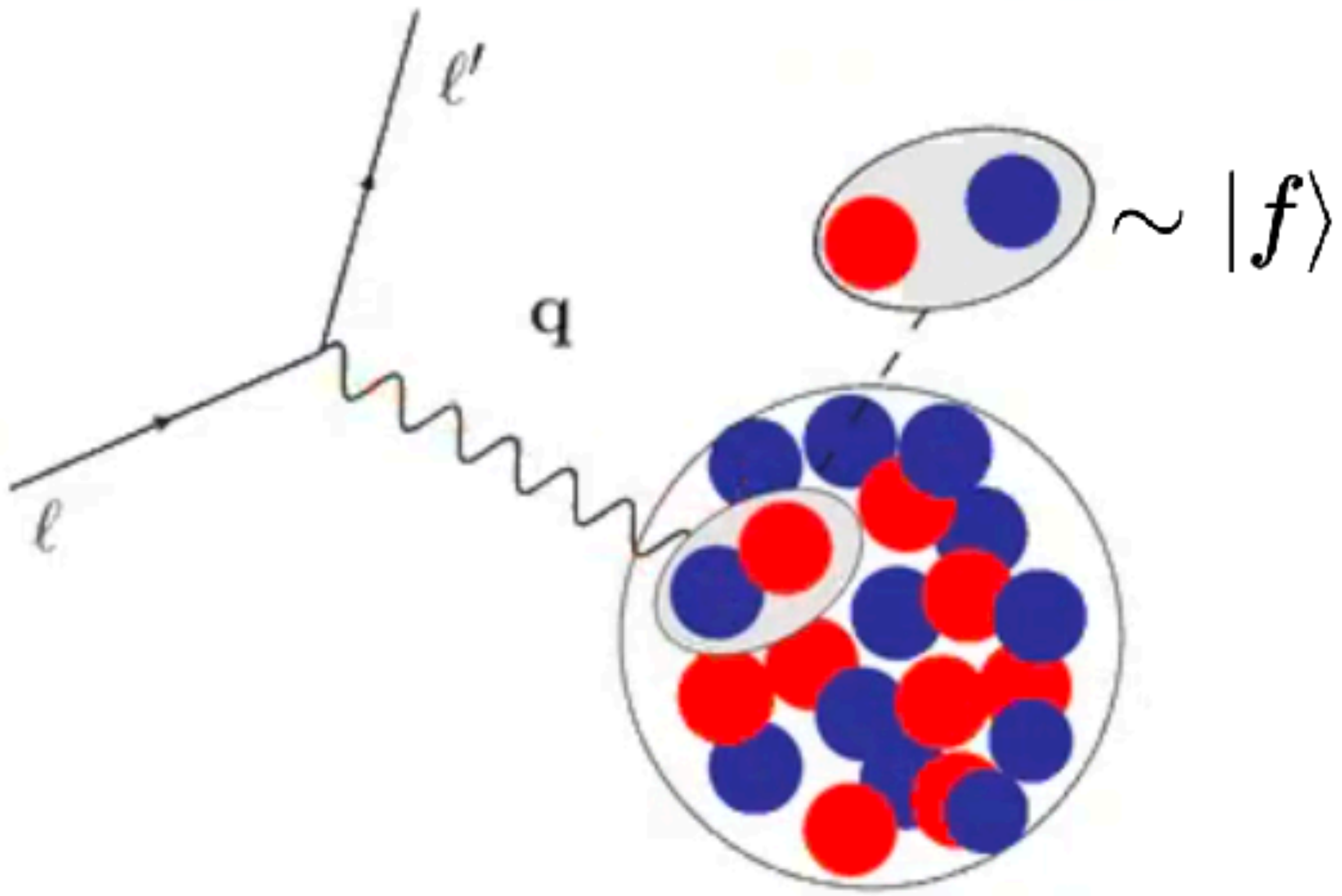
[Phenomenological interactions and currents AV18 + UIX]

L. Andreoli, R. Weiss, G. Chambers-Wall, J. Carlson,
G. B. King, S. Gandolfi, A.G., S. Pastore, M. Piarulli, R. B. Wiringa **[In preparation]**

S. Pastore et al., PRC 101, 044612 (2020)

Short time approximation

$$\frac{d^2\sigma}{d\omega d\Omega} = \sigma_M[v_L R_L(\mathbf{q},\omega) + v_T R_T(\mathbf{q},\omega)]$$



$$R_\alpha(q,\omega) = \sum_f \delta(\omega + E_0 - E_f) |\langle f|O_\alpha(\mathbf{q})|0\rangle|^2$$

$$R_\alpha(q,\omega) = \int_{-\infty}^{\infty} \frac{dt}{2\pi} e^{i(\omega+E_i)t} \langle \Psi_i | O_\alpha^\dagger(\mathbf{q}) e^{-iHt} O_\alpha(\mathbf{q}) | \Psi_i \rangle$$

The sum over all final states is replaced by a two nucleon propagator:

inclusion of full two-body dynamics

see F. Bonaiti talk for a different approach

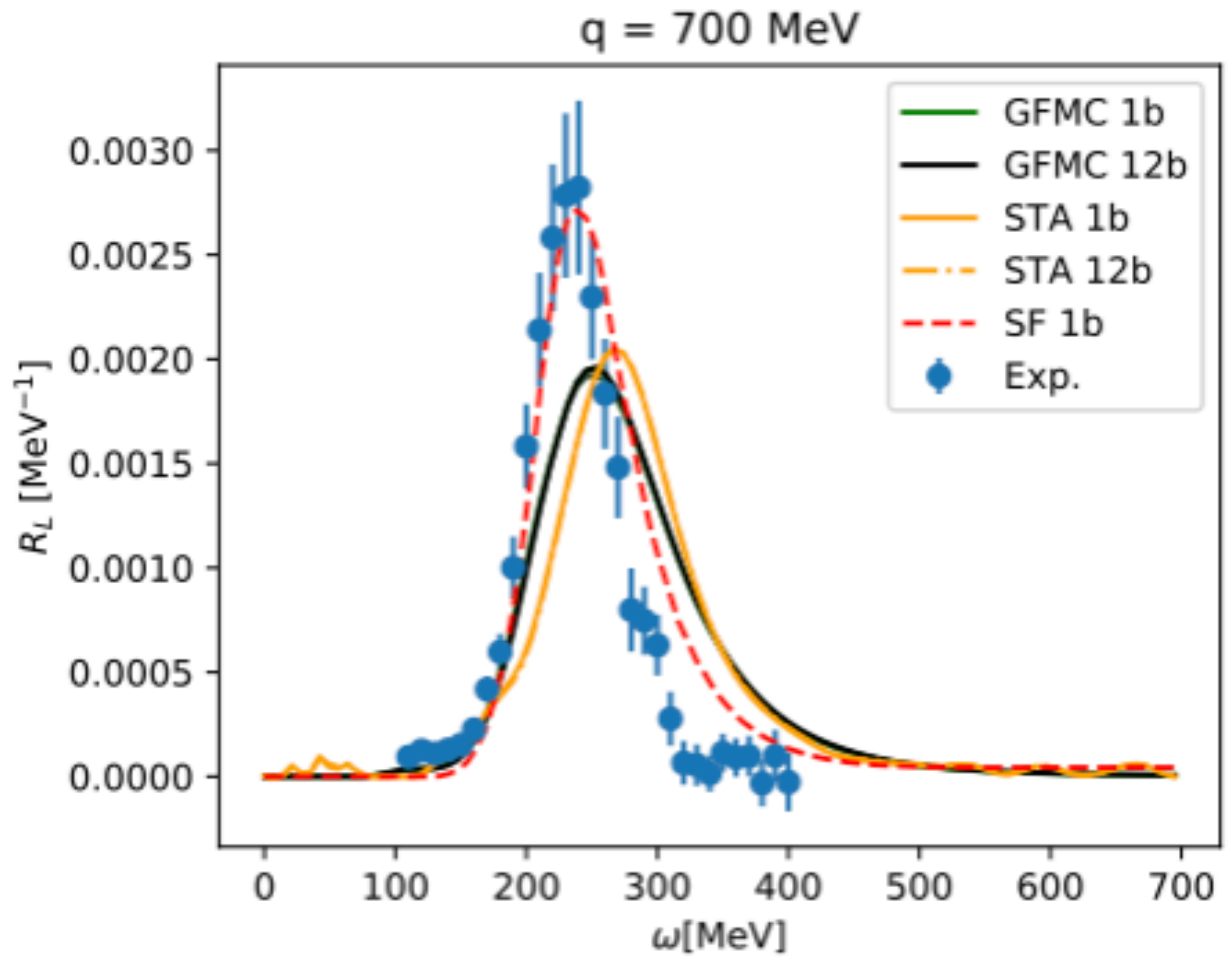
Figures and formulas courtesy of L. Andreoli

L. Andreoli et al., PRC 105, 014002 (2022)

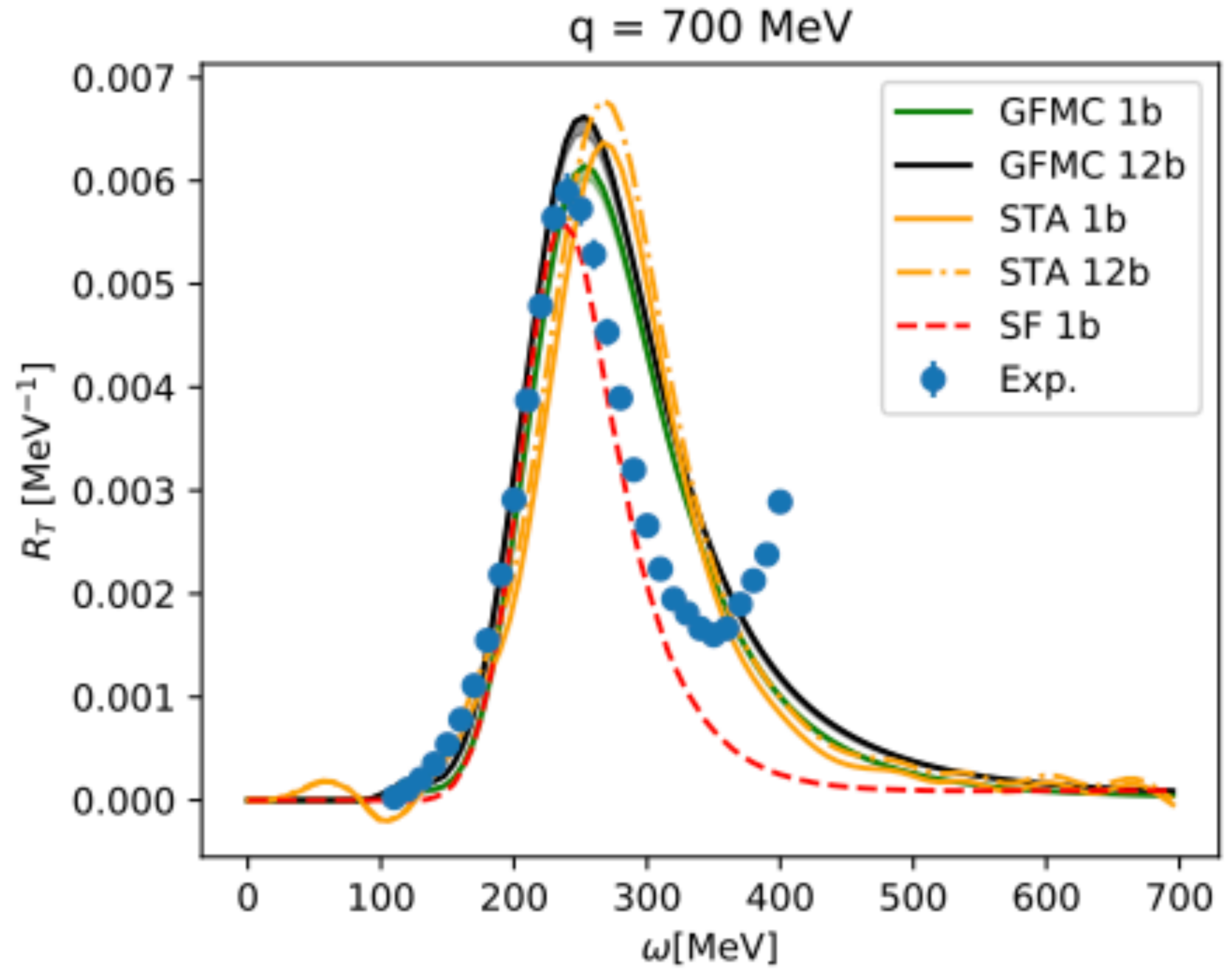
Previous results

- The STA contain the full 2-body dynamics.
- The spectral function can use the full relativistic dynamic exactly.

Correct the STA including (at least partially) the relativistic dynamic and kinematic



Helium-3



Relativistic Currents

Higher momentum transfer

- New expansion of the currents

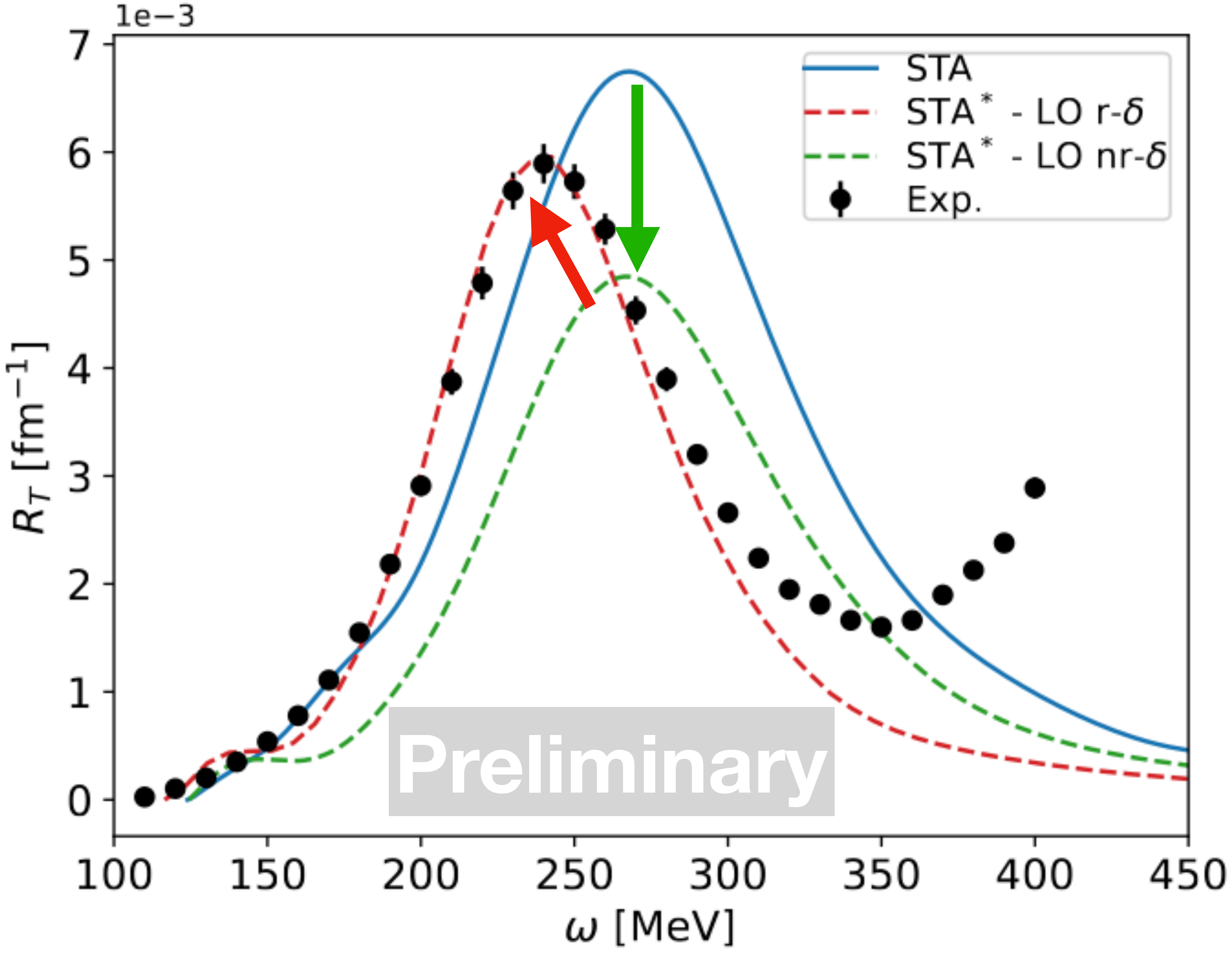
$$\boldsymbol{p}' = \boldsymbol{p} + \boldsymbol{q}$$

$$j^0_{p^0} = \alpha(q) G_E(Q^2_{qe}) e^{i\boldsymbol{q}\cdot\boldsymbol{r}_i}$$

$$\boldsymbol{j}^{\perp}_{p^0} = \frac{2m\tau_{qe}}{q^2} G_M(Q^2_{qe}) \alpha(q) i(\boldsymbol{\sigma} \times \boldsymbol{q}) e^{i\boldsymbol{q}\cdot\boldsymbol{r}_i}$$

- Relativistic treatment of the energy conservation

Helium-3 q=700 MeV/c

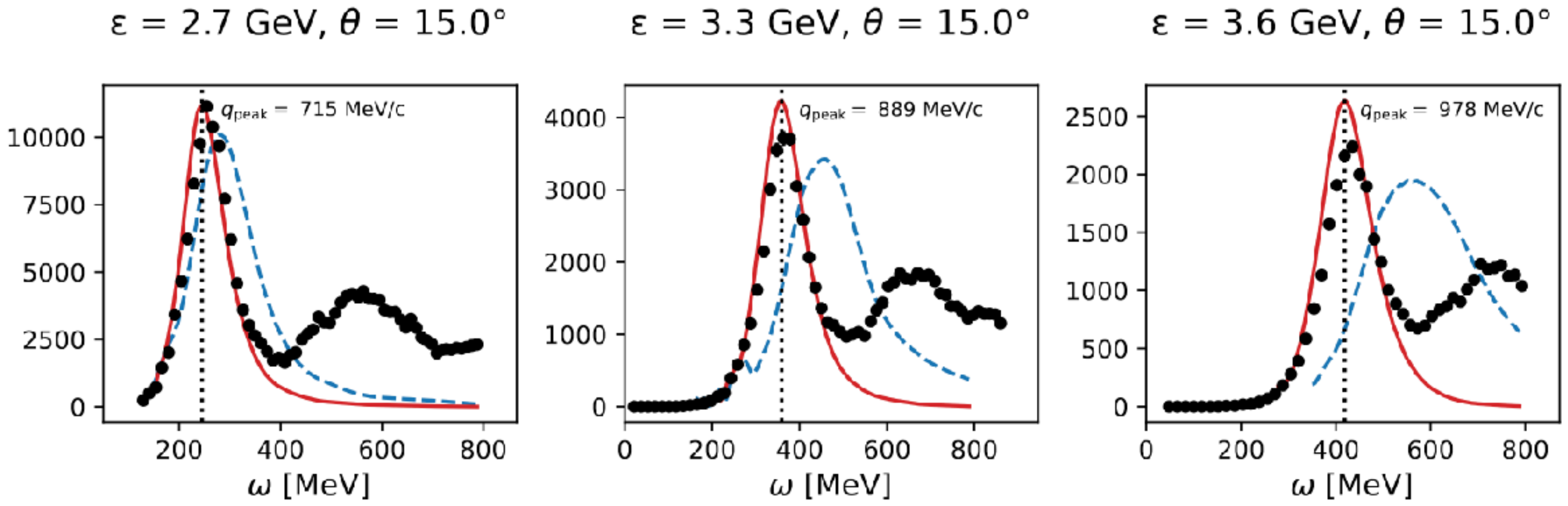


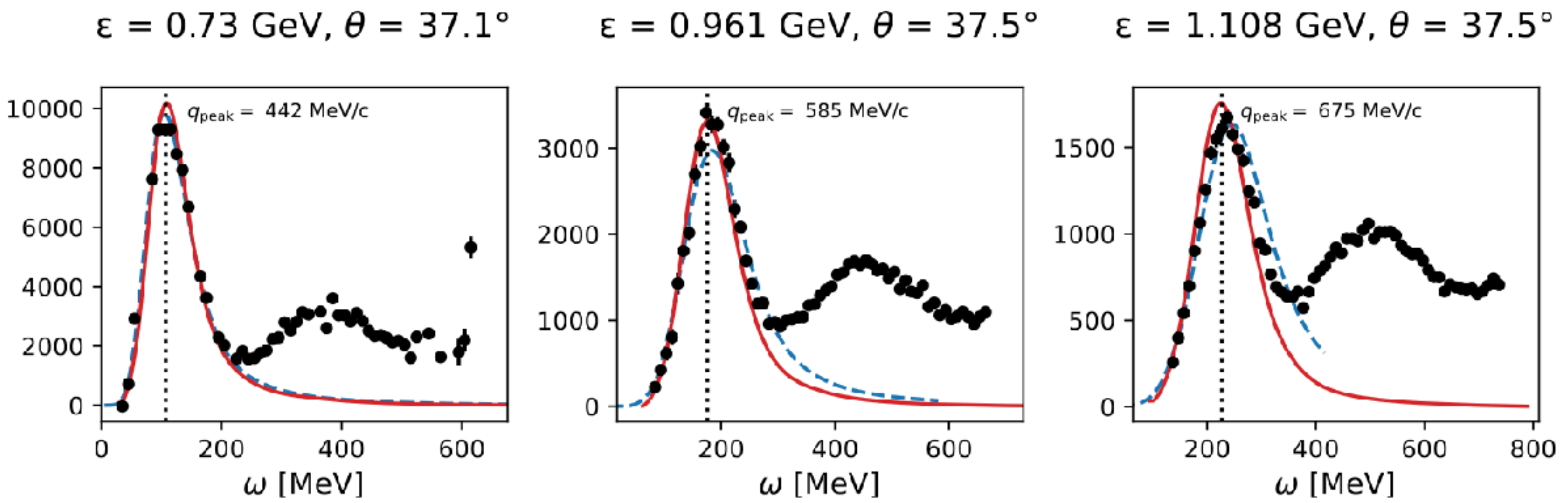
L. Andreoli, R. Weiss et al., in preparation (2025)

New cross sections

AV18+UIX with phenomenological 1-body current

Helium-3





Preliminary

Helium-4

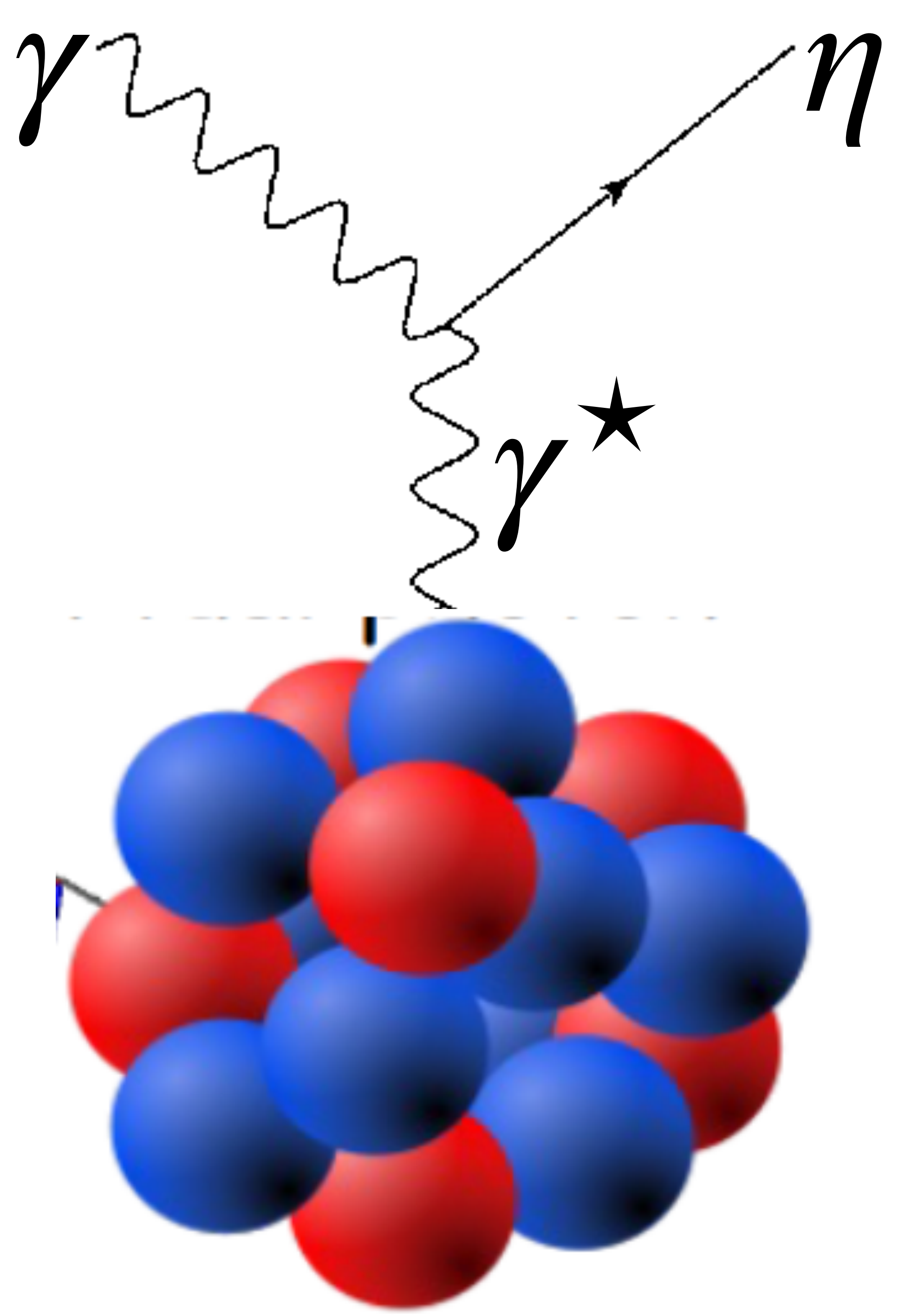
see L. Gan talk on Monday

Primakoff production of η meson: an ab-initio perspective

L. Andreoli, A.G., J. Carlson, G. Chambers-Wall, G. B. King
S. Pastore, M. Piarulli, R. B. Wiringa, R. Weiss

Thanks to
M. Albrecht (JLab)
I. Jaegle (JLab)
D. Smith (JLab)
V. Flechas (FIU)

Primakoff production of η



- Production of neutral mesons from interaction photon - nuclear Coulomb field

- Precision extraction of the lifetime of the η meson

- Modeling based on Glauber theory + FSI + Shadowing (parametrization of the nuclear effects) [1]

- Nuclear structure represents the main challenge

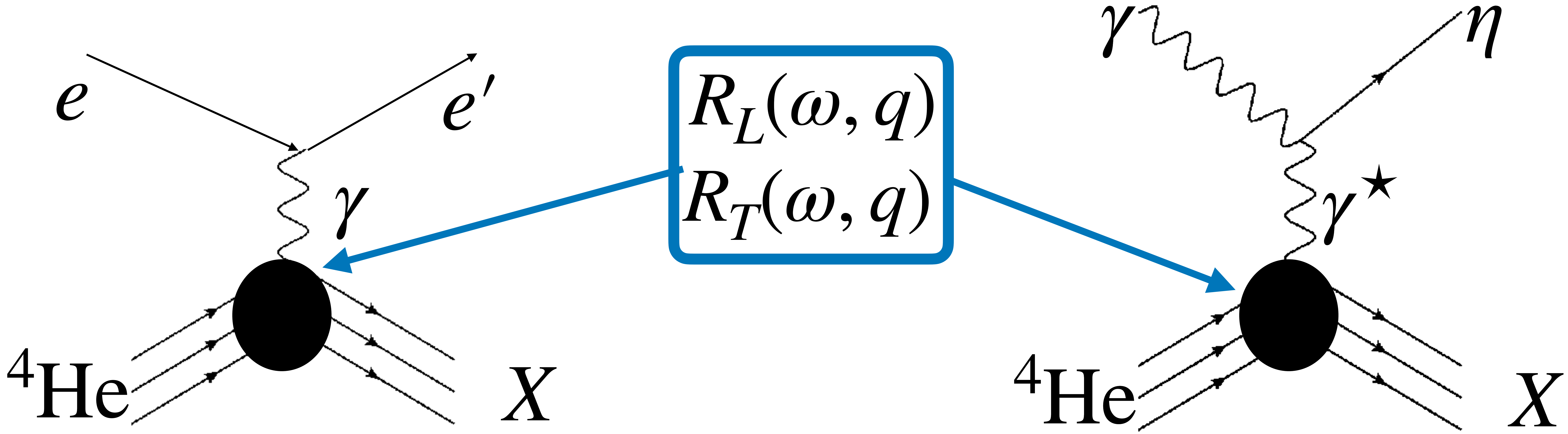
$$\frac{d\sigma}{d\Omega} = \Gamma_{\eta\to\gamma\gamma} \frac{8Z^2\alpha}{m_\eta^3} \frac{|\overrightarrow{k}'|^3 k}{q^4} \sin^2\theta F_A^2(q^2)$$

$$\Gamma_{\eta\to\gamma\gamma} = \frac{\alpha^2}{64\pi^3 f_\pi^2} m_\eta^3 c_\eta^2 \,.$$

[1] S. Gevorkyan et al., Phys. Rev. C **80**, 055201 (2009)

Primakoff production and electro scattering

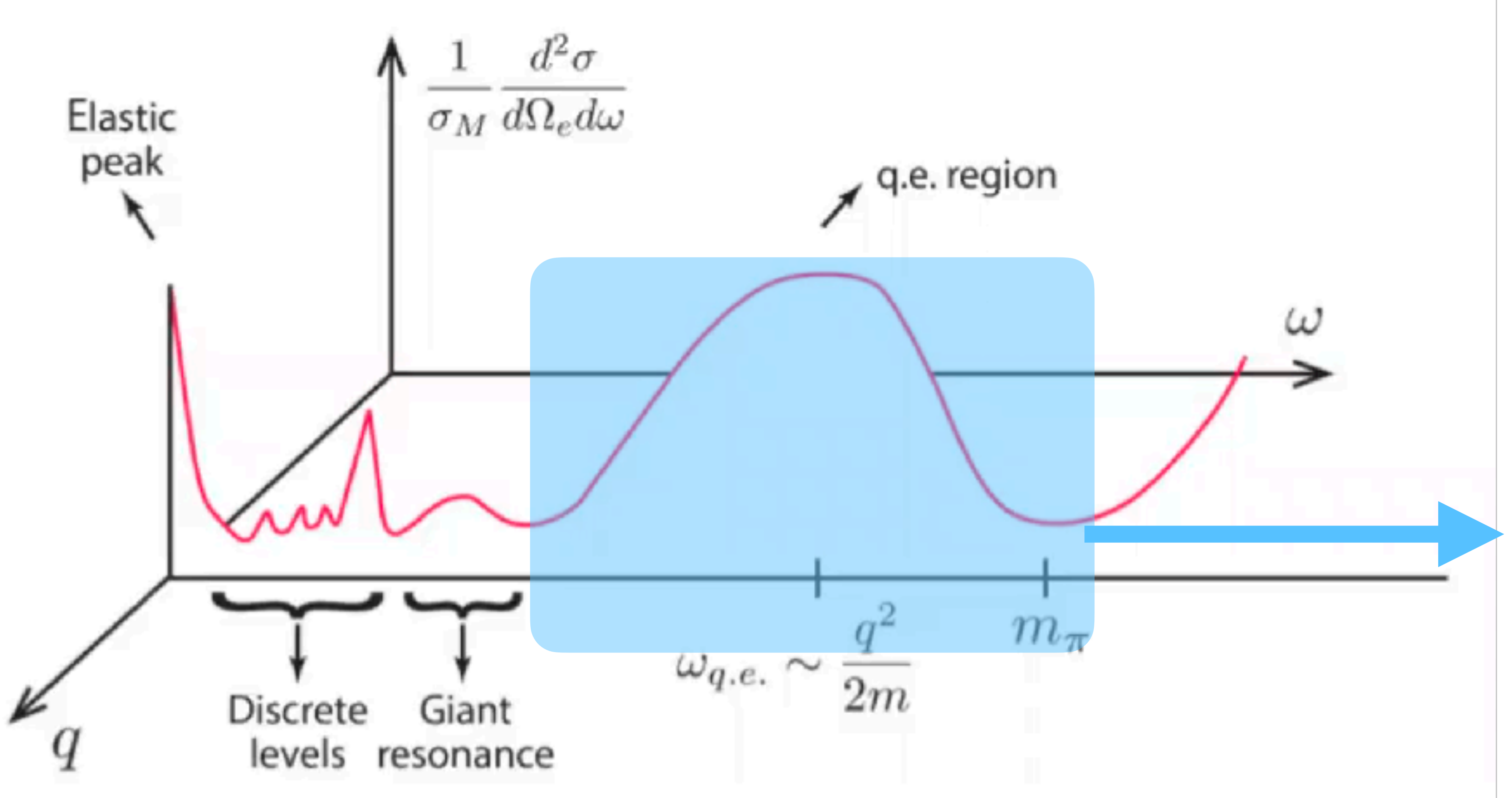
The nuclear vertex in the Primakoff production is identical to the one of electro-scattering



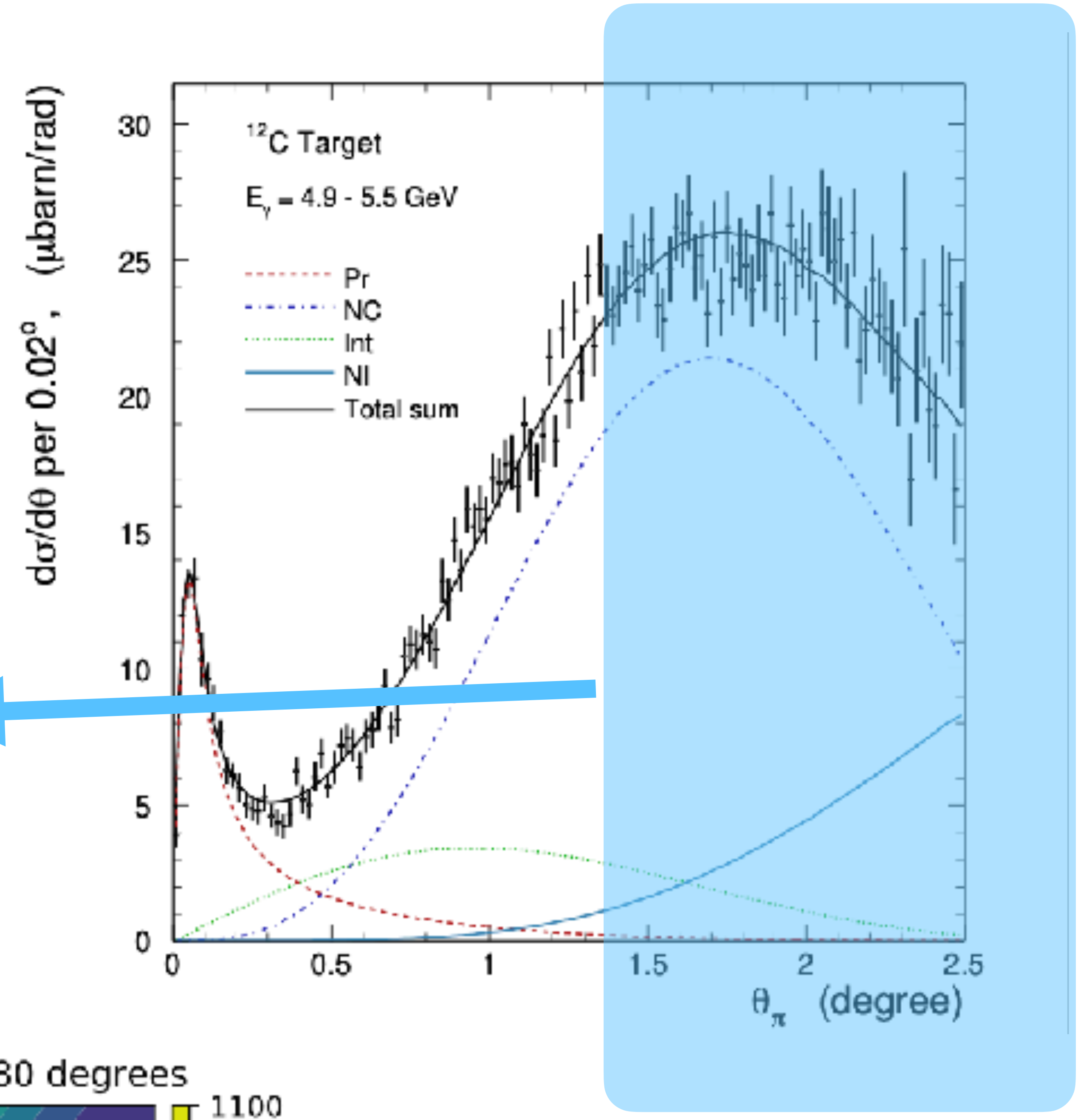
$$\frac{d\sigma}{dE' d\Omega} = \frac{8\alpha^3}{m_\eta^3}\Gamma_{\eta\to\gamma\gamma}\frac{|\boldsymbol{k}'|^3 k}{q^4}\sin^2\theta\left(\frac{q^4}{|\boldsymbol{q}|^4}R_L(\omega,|\boldsymbol{q}|) - \left(\frac{q^2}{2|\boldsymbol{q}|^2} + \frac{(k\cdot k')^2}{|\boldsymbol{k}\times\boldsymbol{k}'|^2}\right)R_T(\omega,|\boldsymbol{q}|)\right)$$

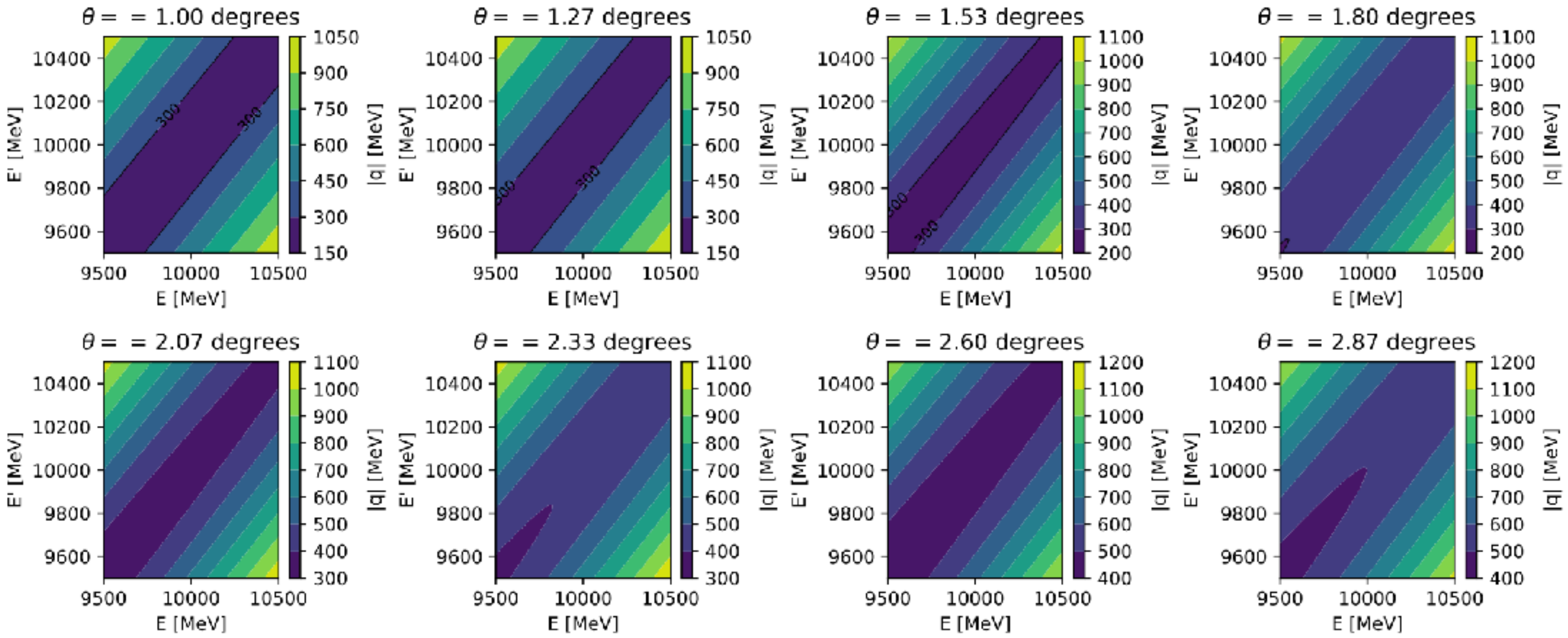
Kinematic and STA

Phys.Rev.Lett. 106, 162303 (2011)



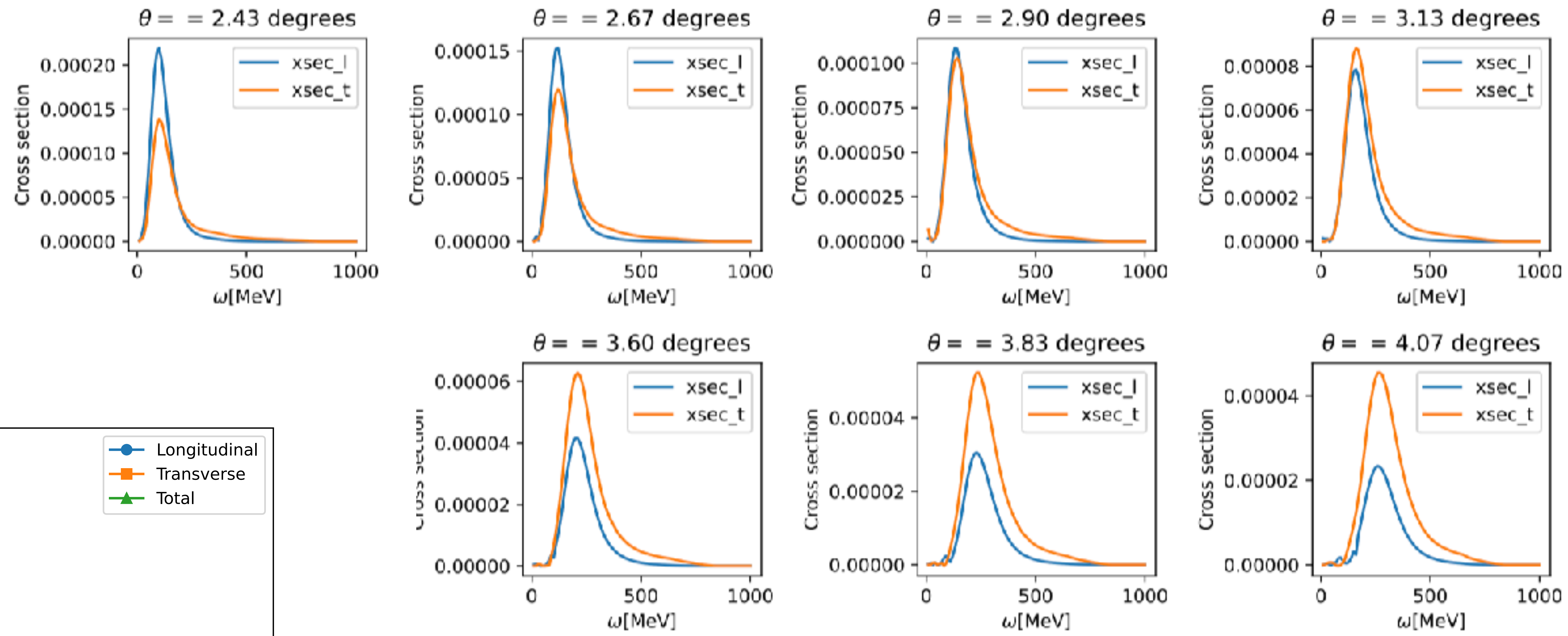
STA + relativistic correction kinematic validity region

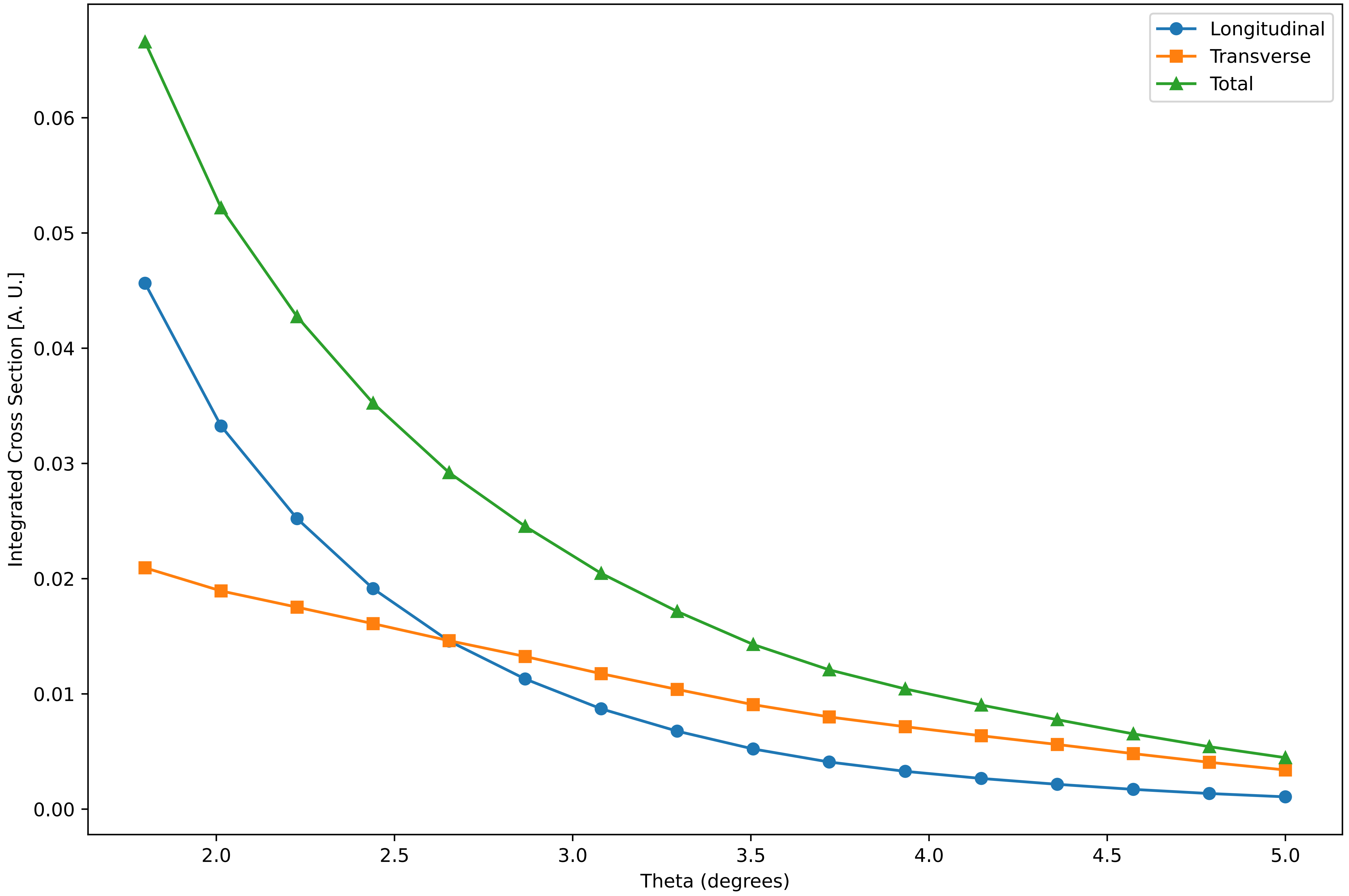




Cross sections

Super Preliminary



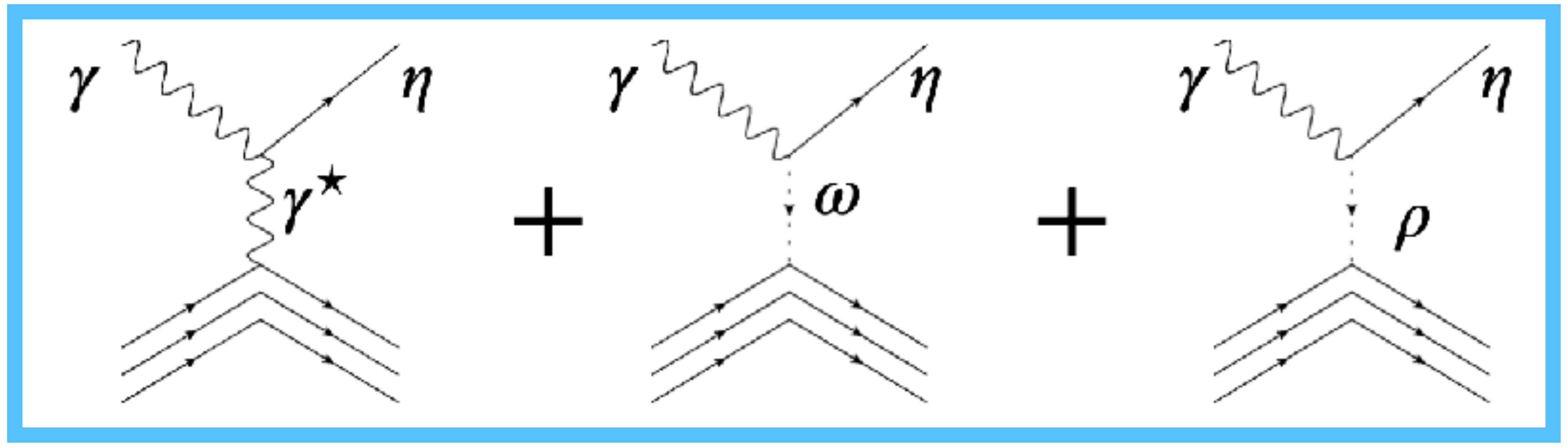


The cross sections are integrated over the energy of the incoming photon and the outgoing meson

Not so easy…

Vector meson dominance and final/initial state interactions

- Vector meson dominance ⟶ New form factors (from Regge theory)



$$\rightarrow j_0 = \sum_{i=1,A} \frac{A^S(q^2, s) + A^V(q^2, s)\tau_z^i}{2} e^{i\mathbf{q}\cdot\mathbf{r}_i}$$

- Final state interactions and Shadowing

Modification of the plane wave of the outgoing meson and incoming photon

$$e^{i\mathbf{k}\cdot\mathbf{r}_i} \rightarrow e^{i\mathbf{k}\cdot\mathbf{r}_i}\chi_{\mathbf{k}}(\mathbf{r}_i)$$

Summary I

- **First ab-initio calculation of magnetic and charge form factors of nuclei $7 \leq A \leq 10$.**

  - Good overall agreement with the experimental data.
  - Two-body currents account up to 40-50% of the total contribution to the magnetic form factors. Almost negligible for the charge
  - First observation of M_1/M_3 inversion in mirror p-shell nuclei (not observed experimentally yet).
  - Extraction of magnetic and charge radii.

More precise data on more nuclei would permit to constrain better our models

Summary II

- **Short-time approximation responses are in good agreement with the data**
  - New relativistic currents and kinematical effects extend the range of calculations at higher values of q.
  - Accounts for two-body physics both currents and correlations and it is promising to be extended beyond $A \geq 12$.
- **STA responses can be used to compute cross section of π^0, η, η'**
  - Full inclusion of the nuclear dynamics.
  - Inclusion of VMD, FSI and Shadowing is in progress.

Collaborators

L. Andreoli (JLab & ODU)
J. Carlson (LANL)
G. Chambers-Wall (WashU)
S. Gandolfi (LANL)
G. B. King (WashU)
M. Piarulli (WashU)
R. Schiavilla (Retired)
R. B. Wiringa (ANL)
R. Weiss (WashU)

Acknowledgments

NTNP
DOE Topical Collaboration

U.S. DEPARTMENT OF ENERGY

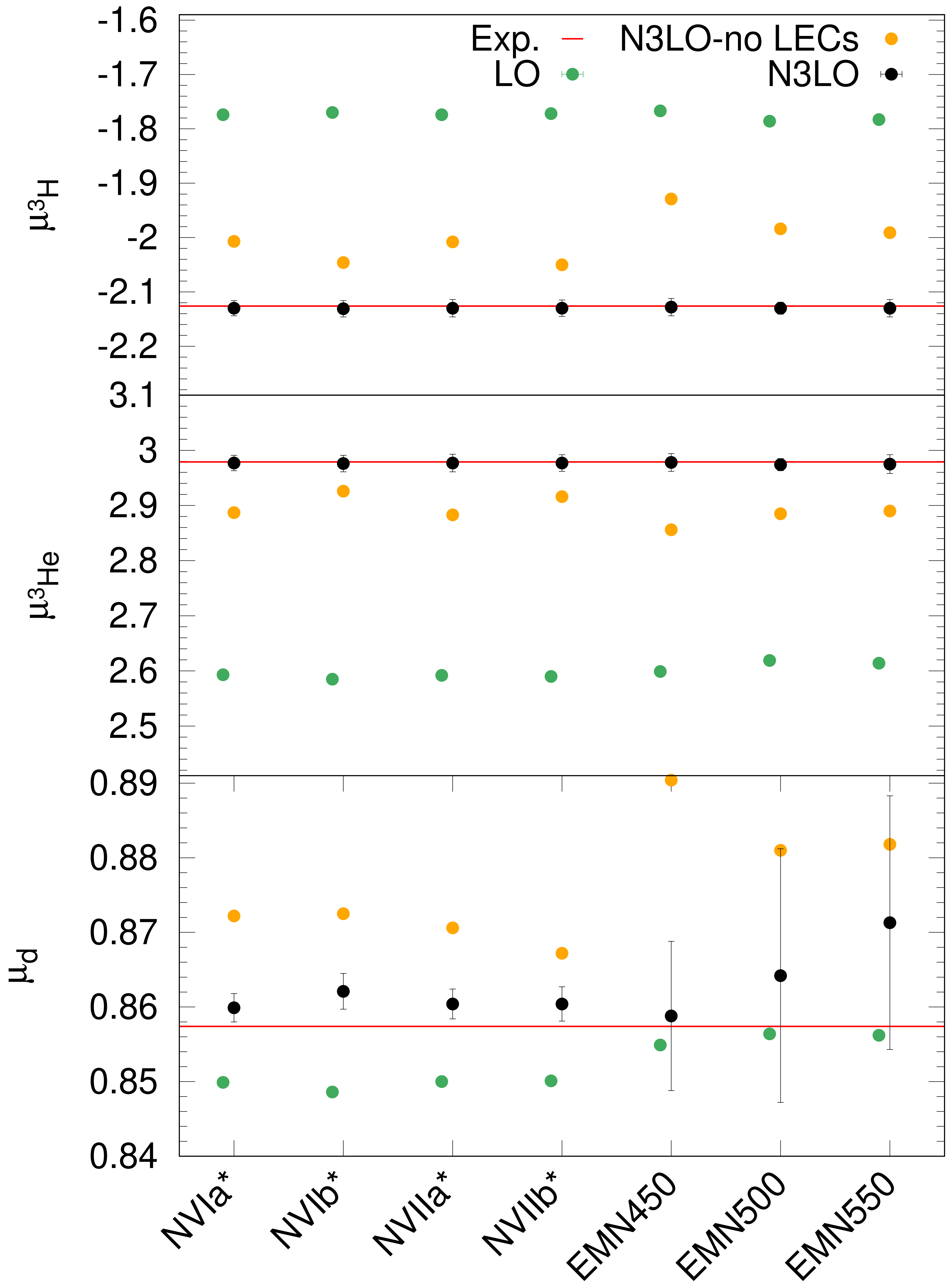
NERSC National Energy Research Scientific Computing Center

Sparse

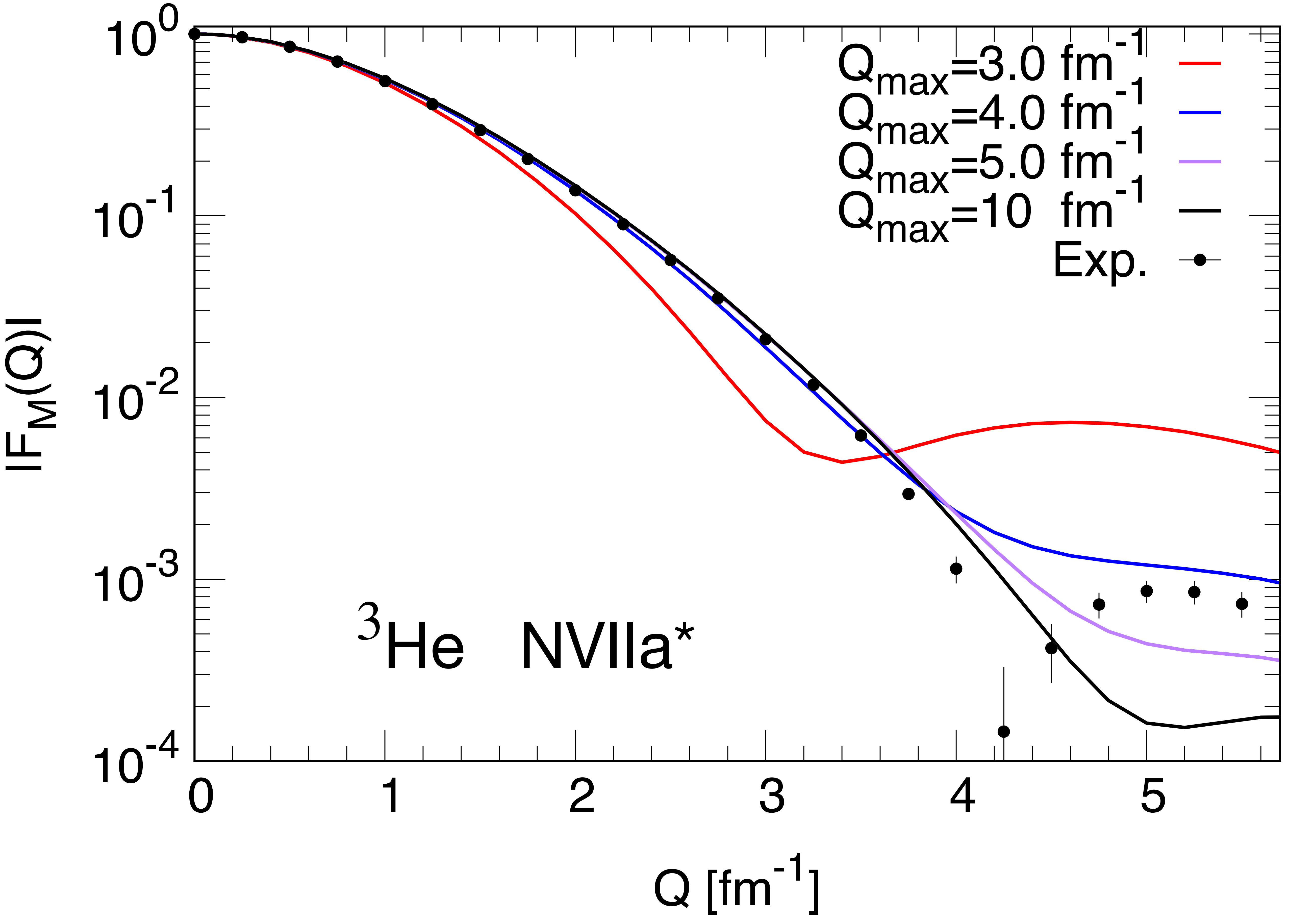
Results of the fit

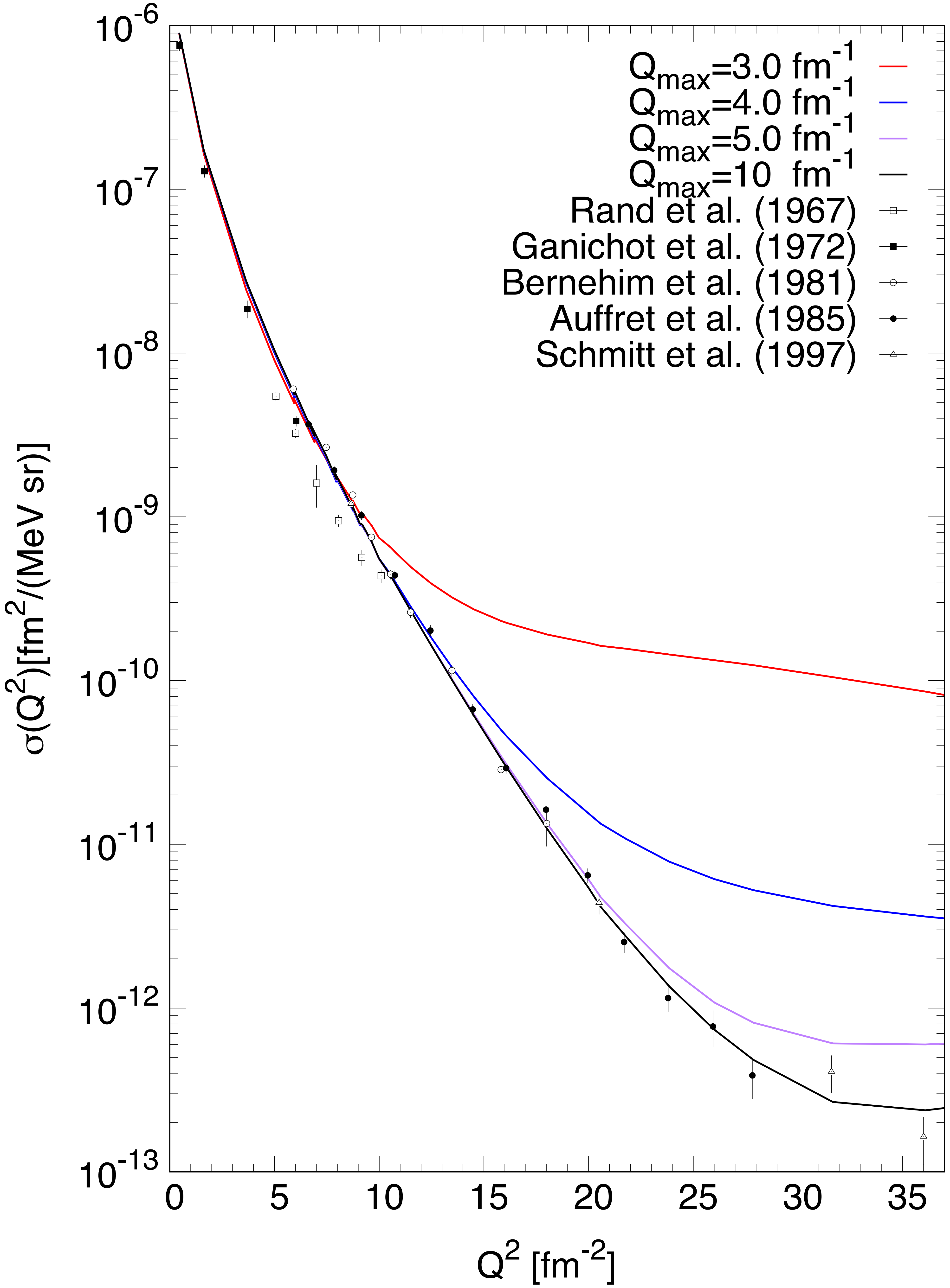
Pot.	χ^2/ndf	χ^2/ndf (no Rand)
NVIa*	9.9	2.0
NVIb*	10.2	2.3
NVIIa*	11.6	2.5
NVIIb*	11.6	2.6
EMN450	11.3	2.8
EMN500	14.7	4.7
EMN550	17.7	7.9

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

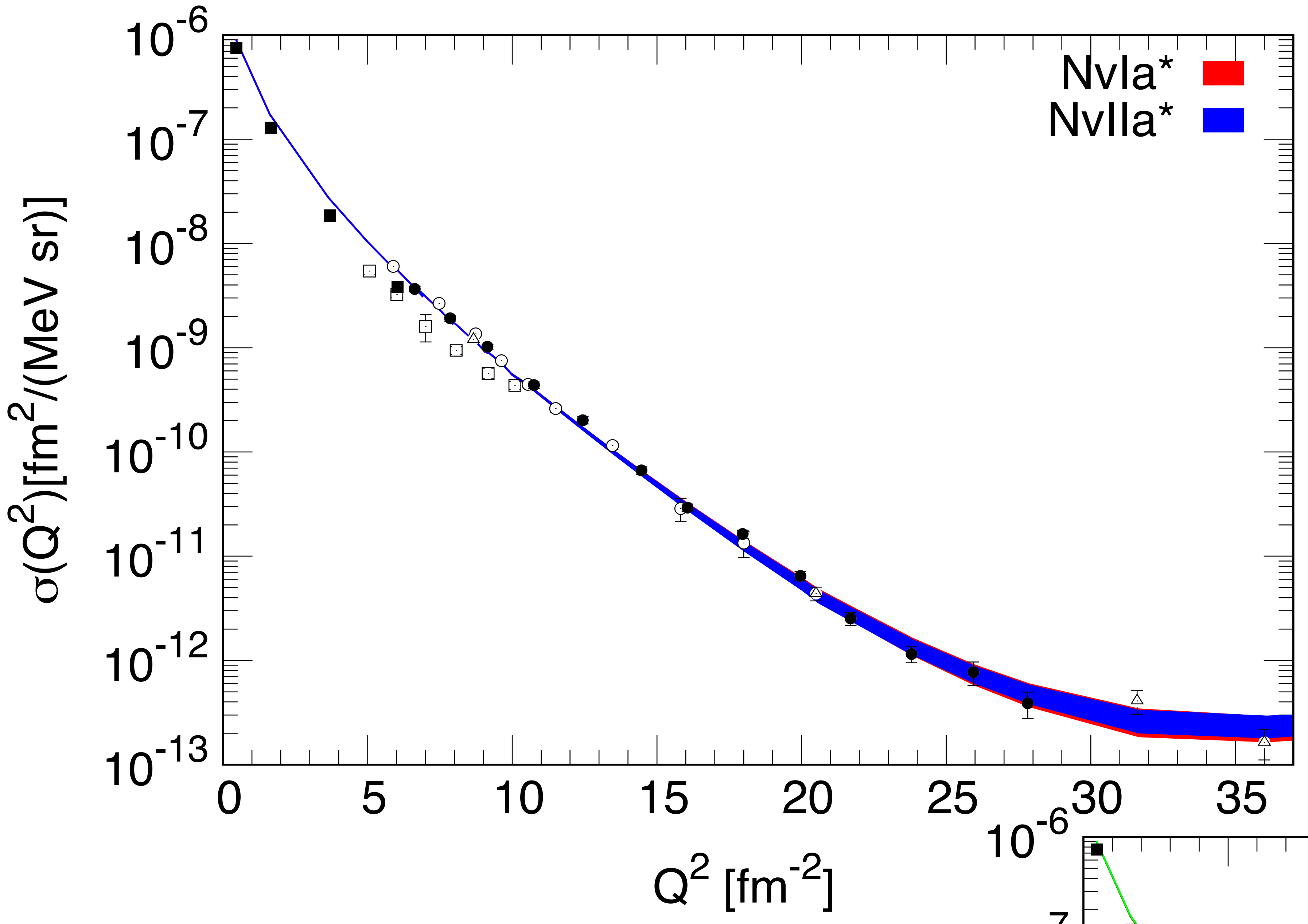


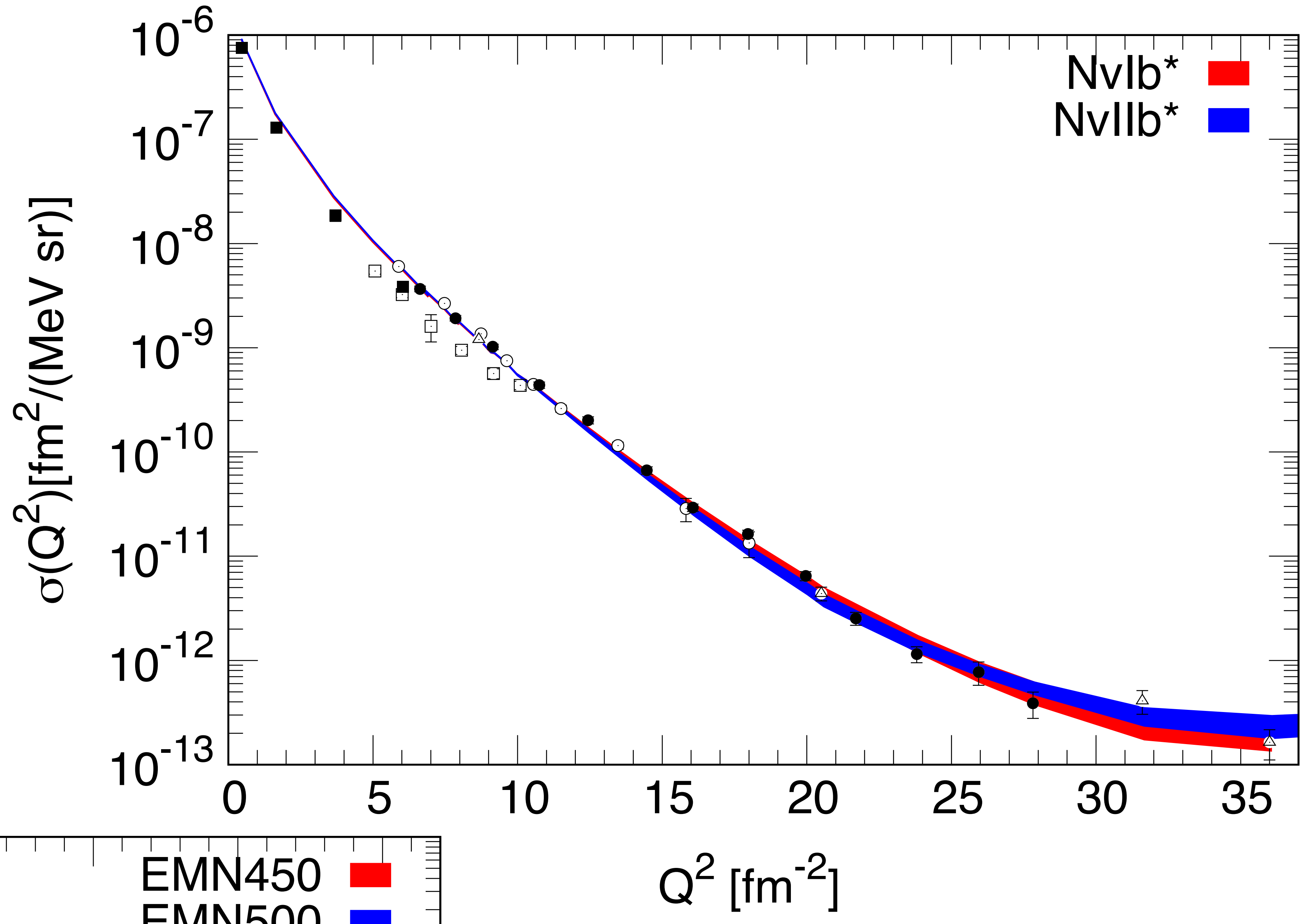
Dependence on $Q^2_{\max}$

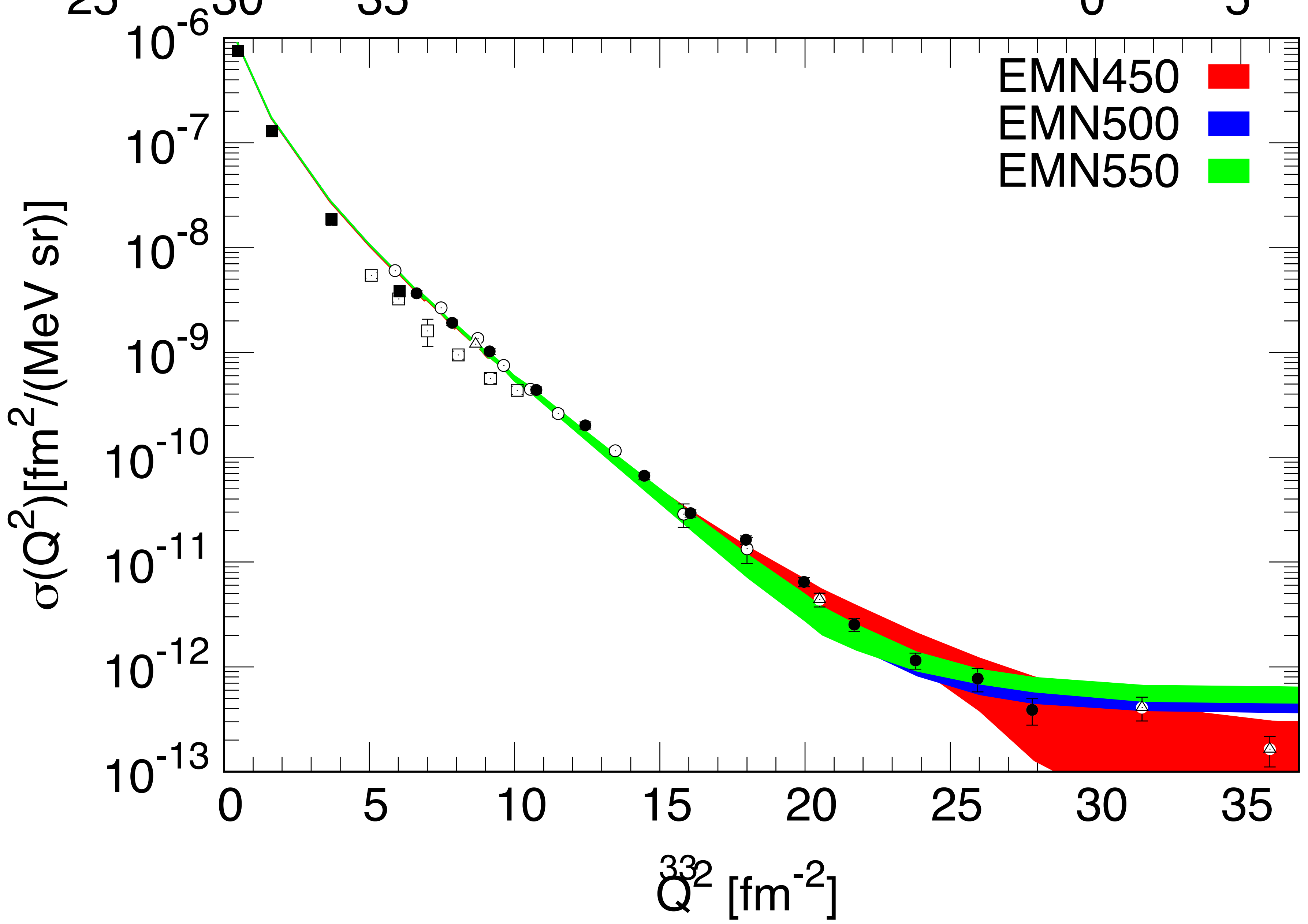




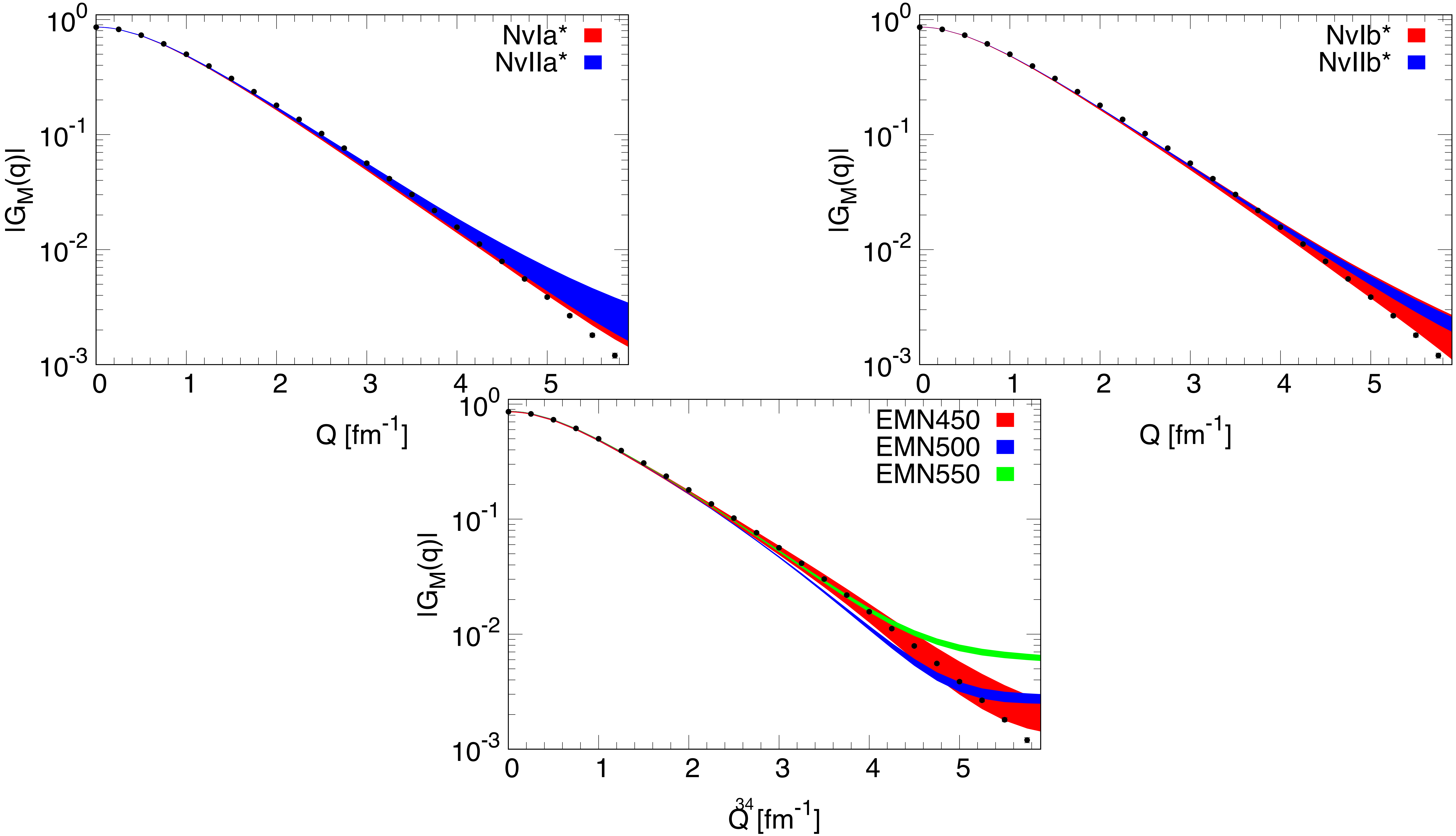
d-threshold


NvIa*
NvIIa*
σ(Q²)[fm²/(MeV sr)]
Q² [fm⁻²]

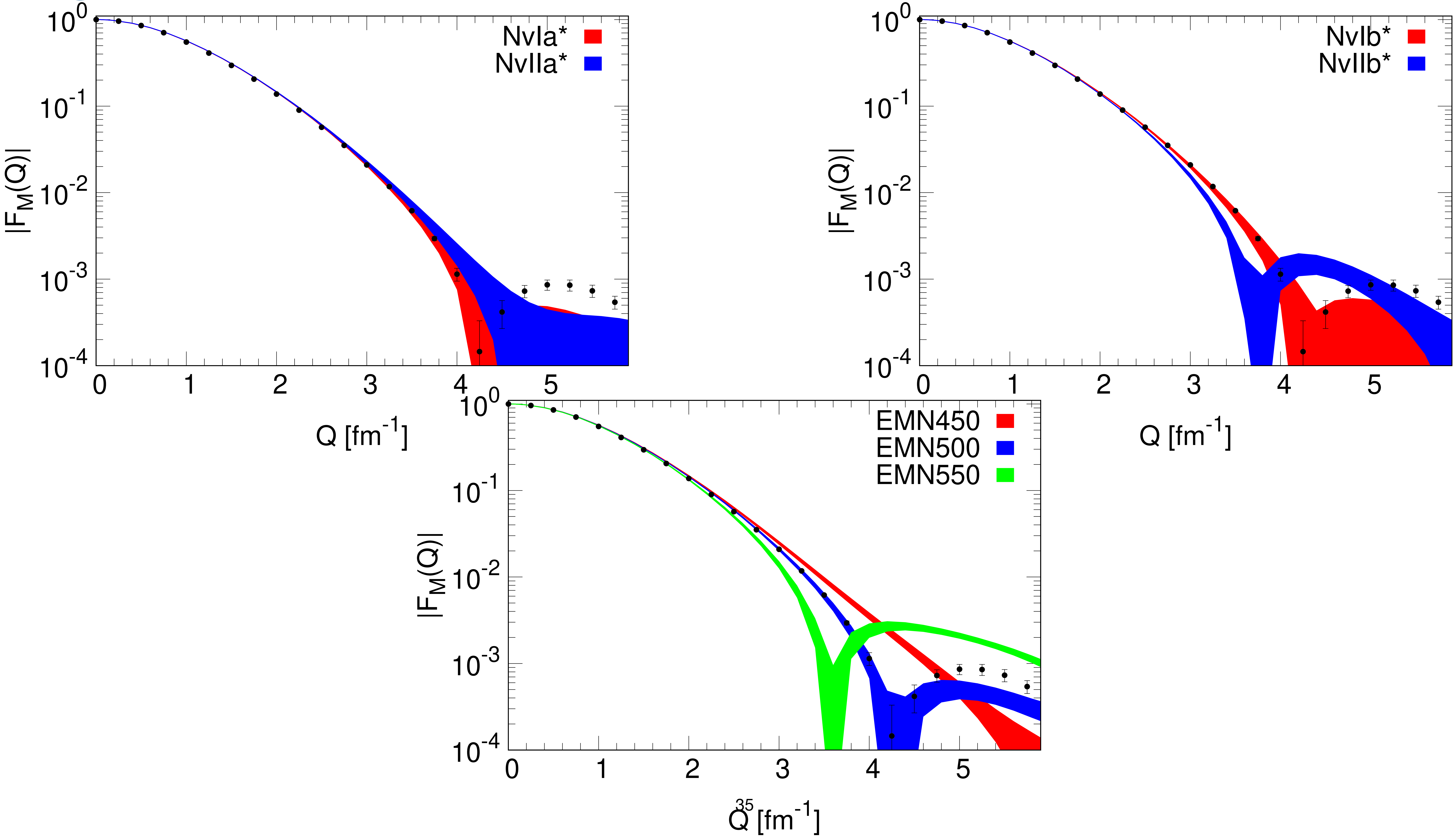

NvIb*
NvIIb*
σ(Q²)[fm²/(MeV sr)]
Q² [fm⁻²]


EMN450
EMN500
EMN550
σ(Q²)[fm²/(MeV sr)]
Q² [fm⁻²]

Magnetic form factors of ^{2}H



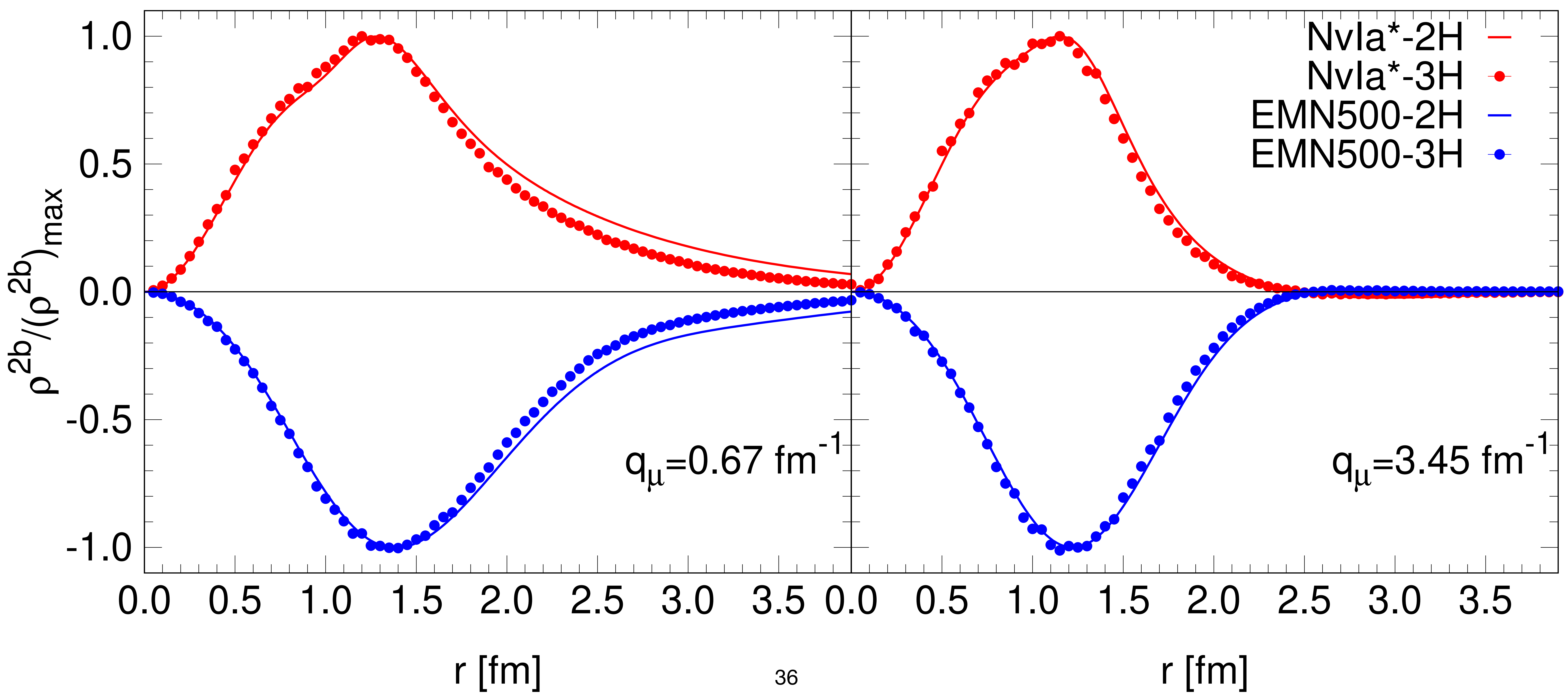
Magnetic form factors of ^{3}He



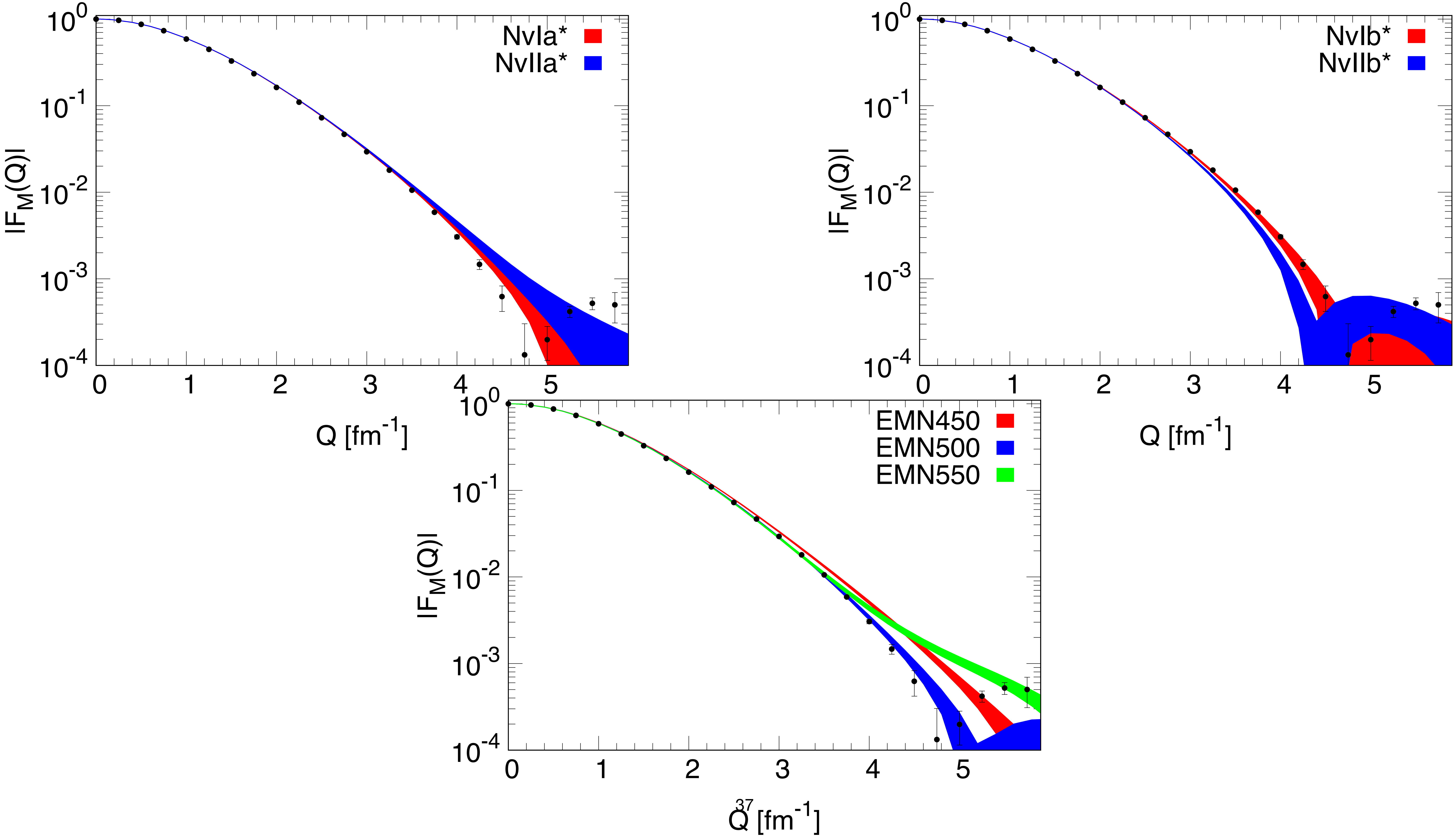
Why does it work?

Universal behavior of isovector transitions

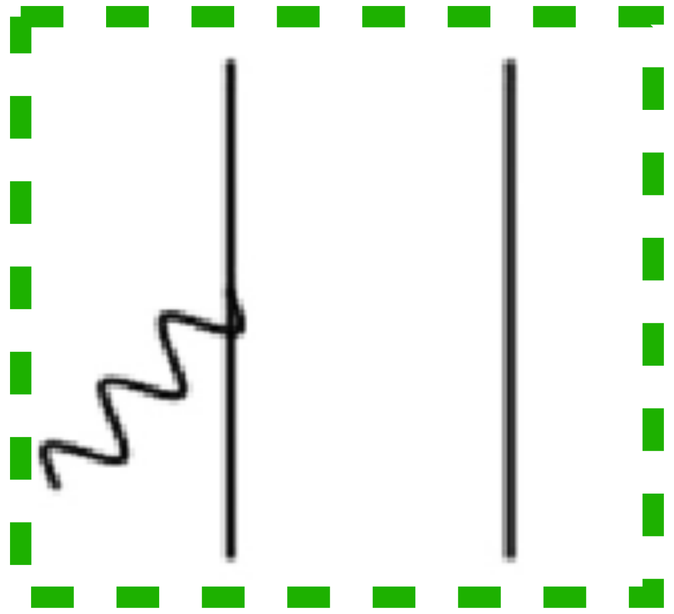
Correlated np pairs ⟷ Universal 2-body wave functions ⟷ Universal 2-body transition densities

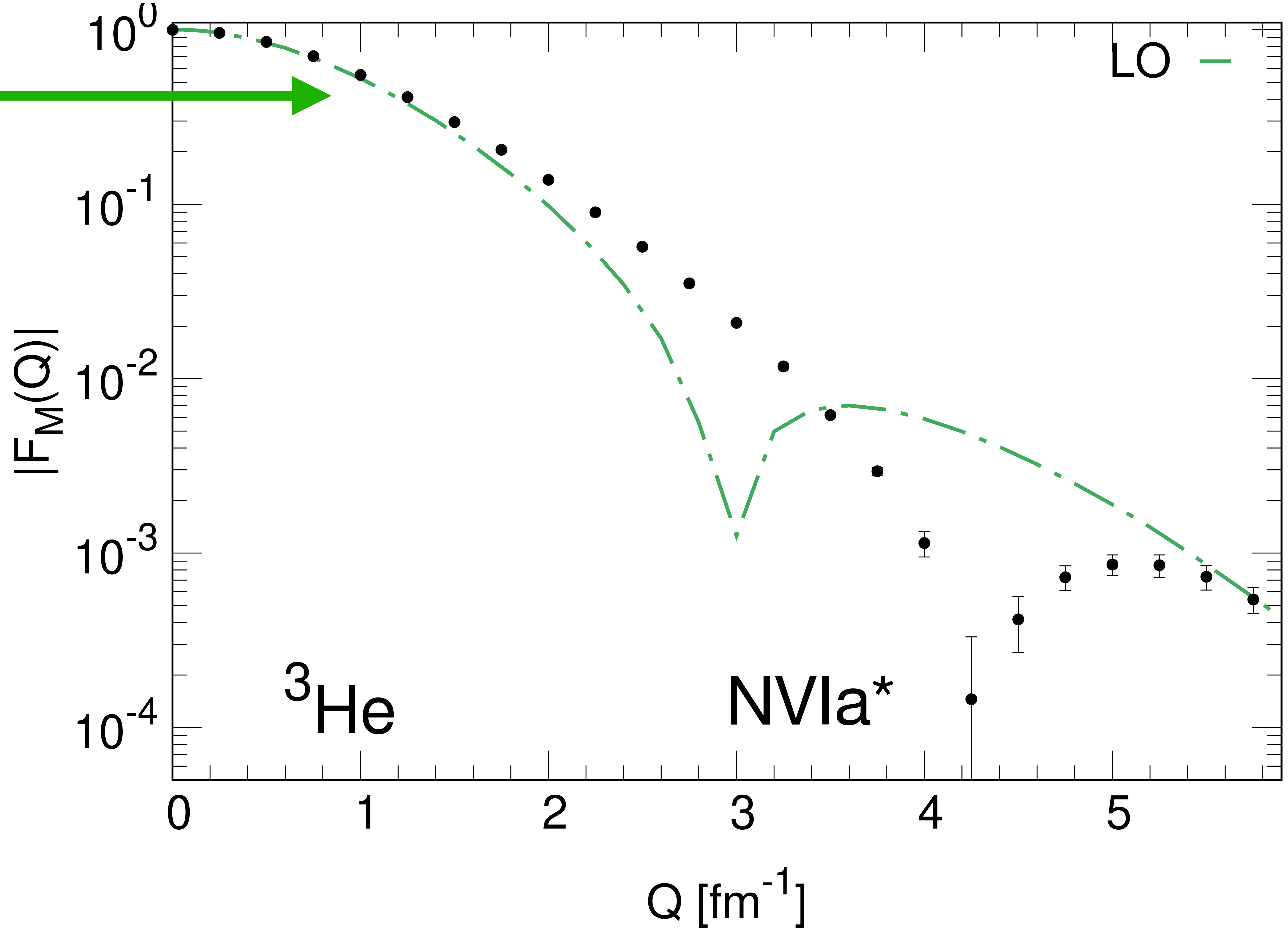


Magnetic form factors of ^{3}H

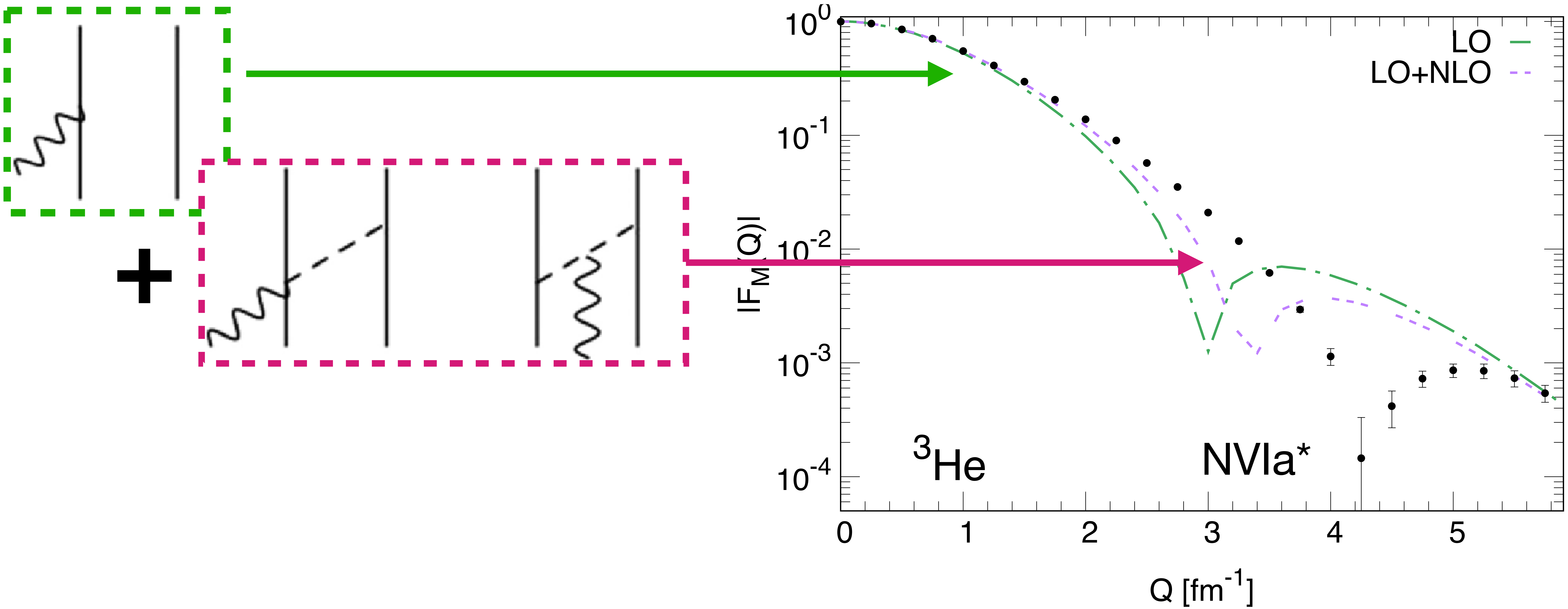


Prediction of A=3 Magnetic Form Factors

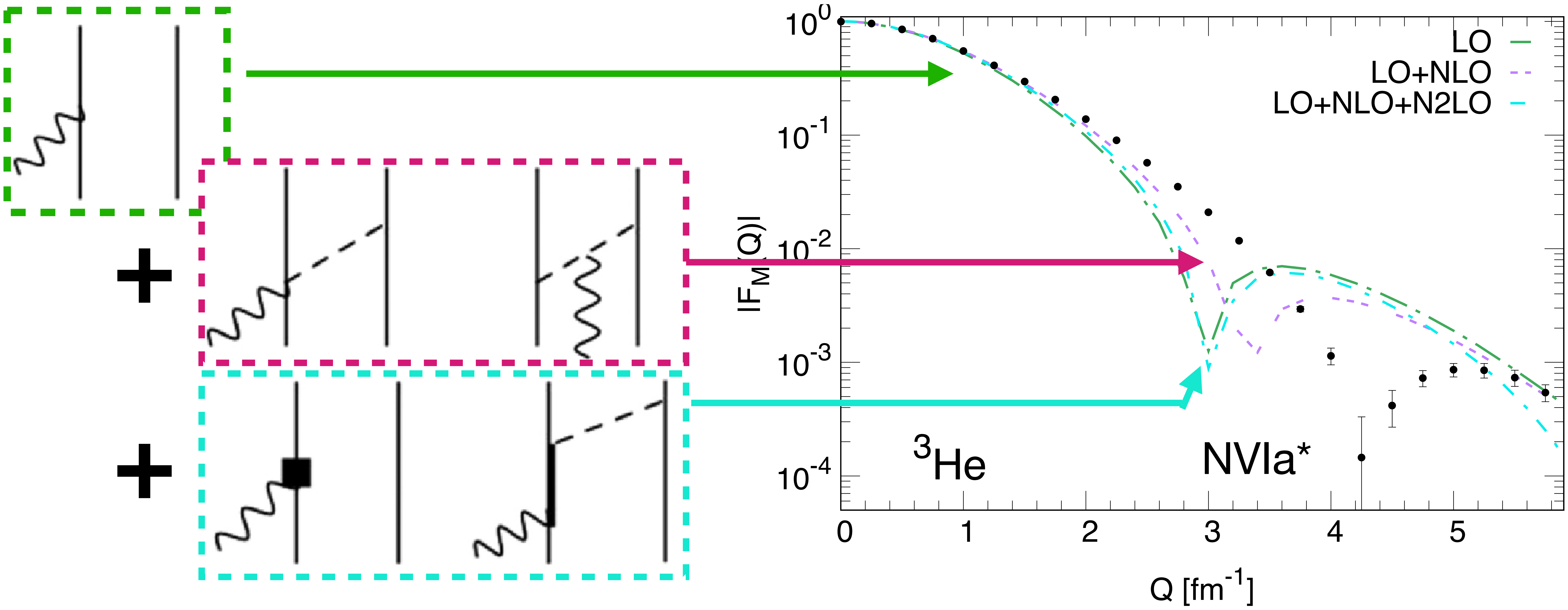




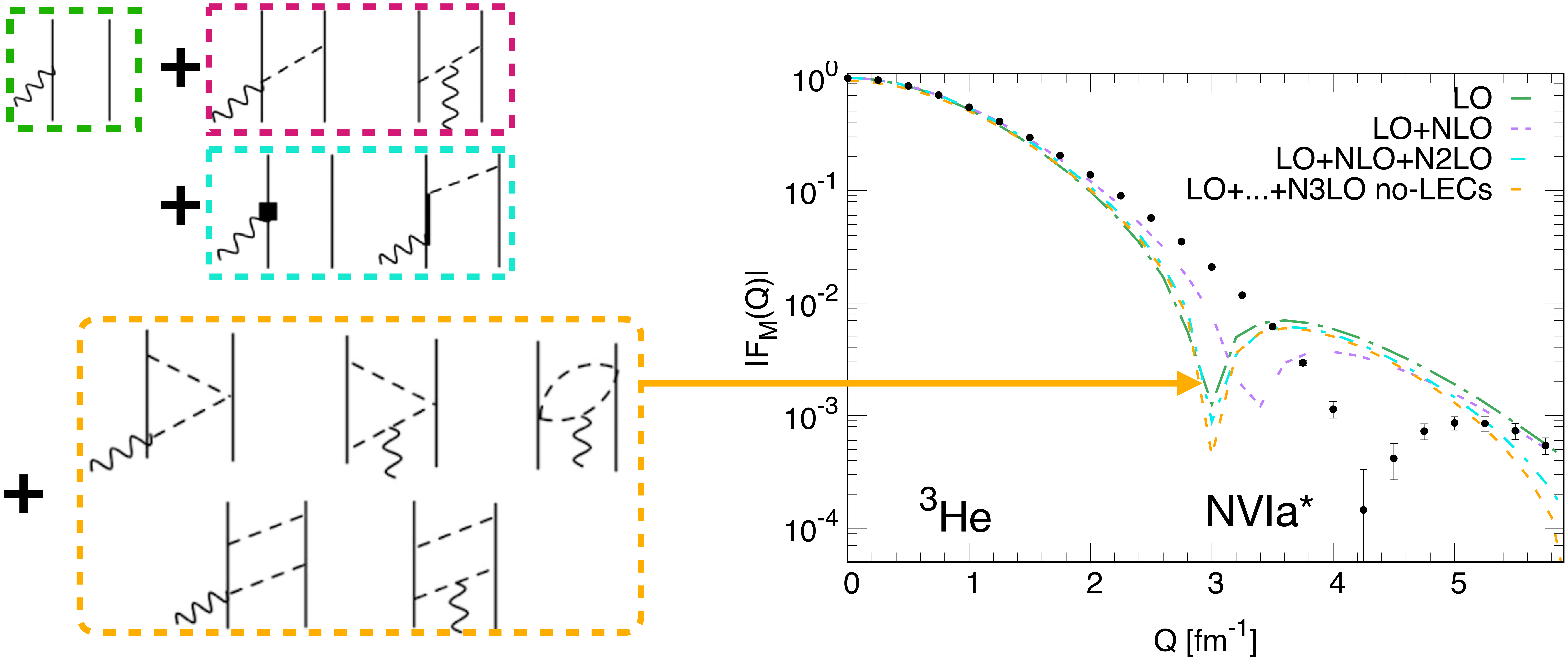
Prediction of A=3 Magnetic Form Factor



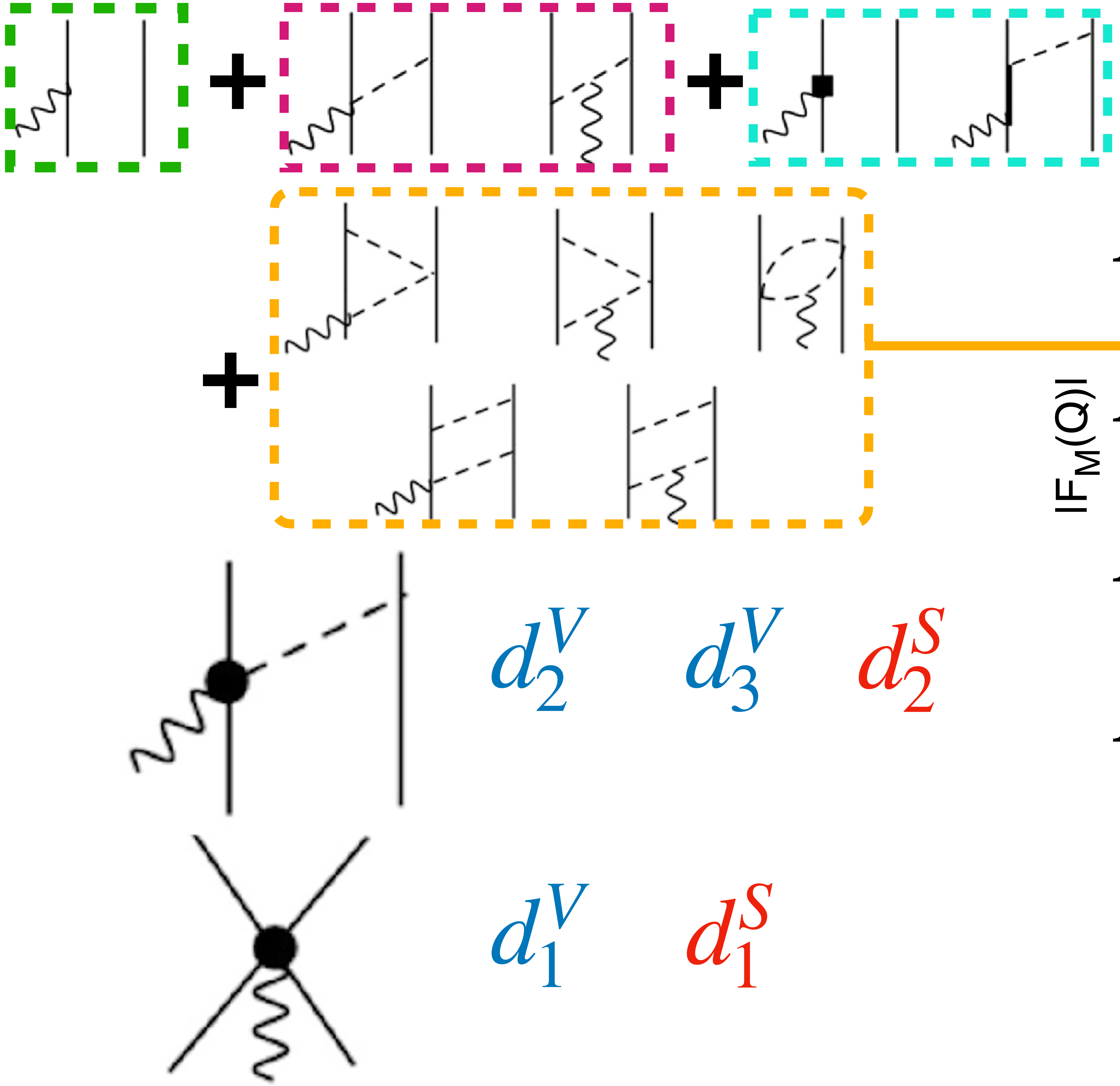
Prediction of A=3 Magnetic Form Factor



Prediction of A=3 Magnetic Form Factor

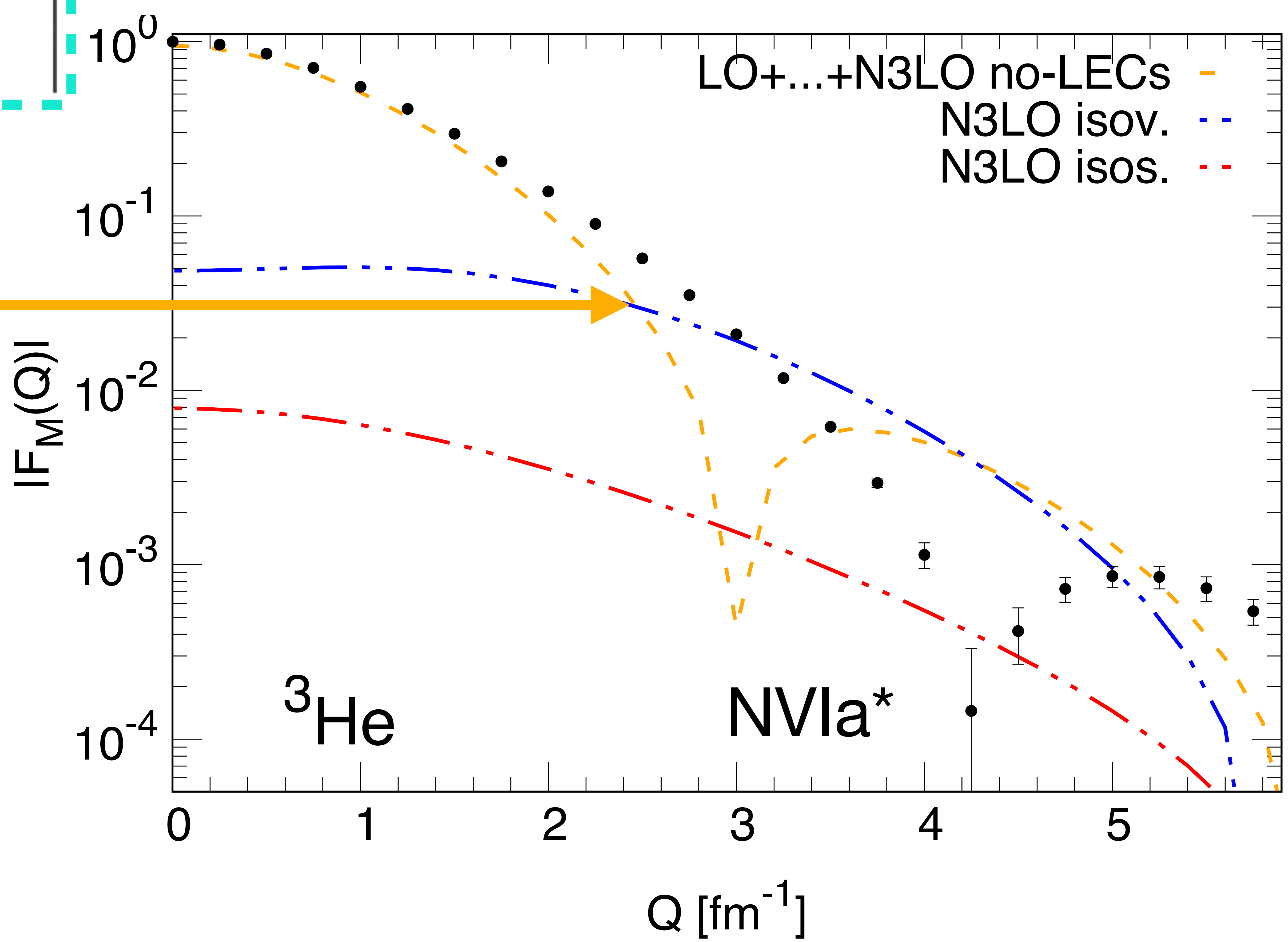


Prediction of A=3 Magnetic Form Factor



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?

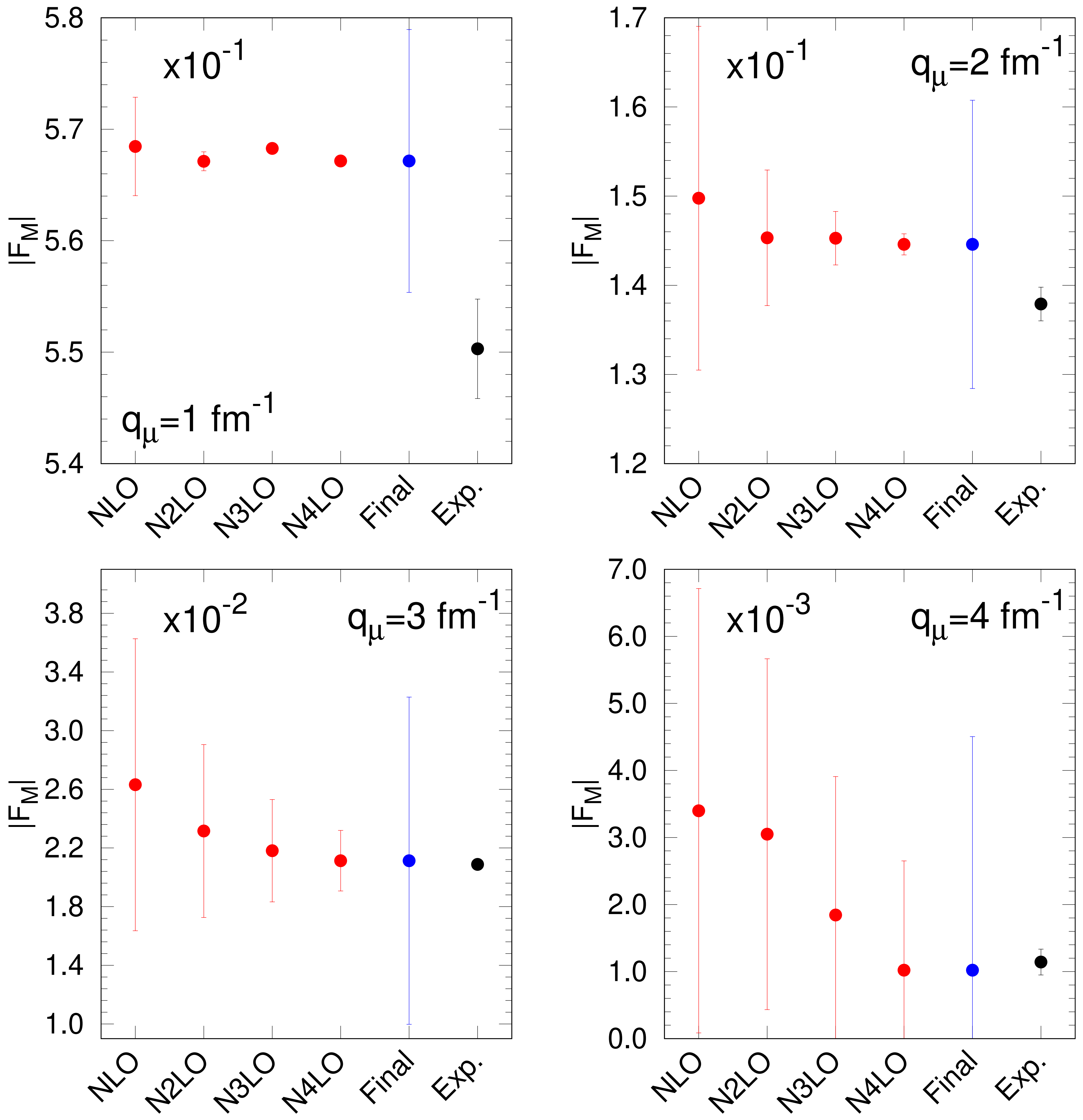
- Truncation errors (as [EPJA 51, 53 (2015)])

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

- 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)])

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

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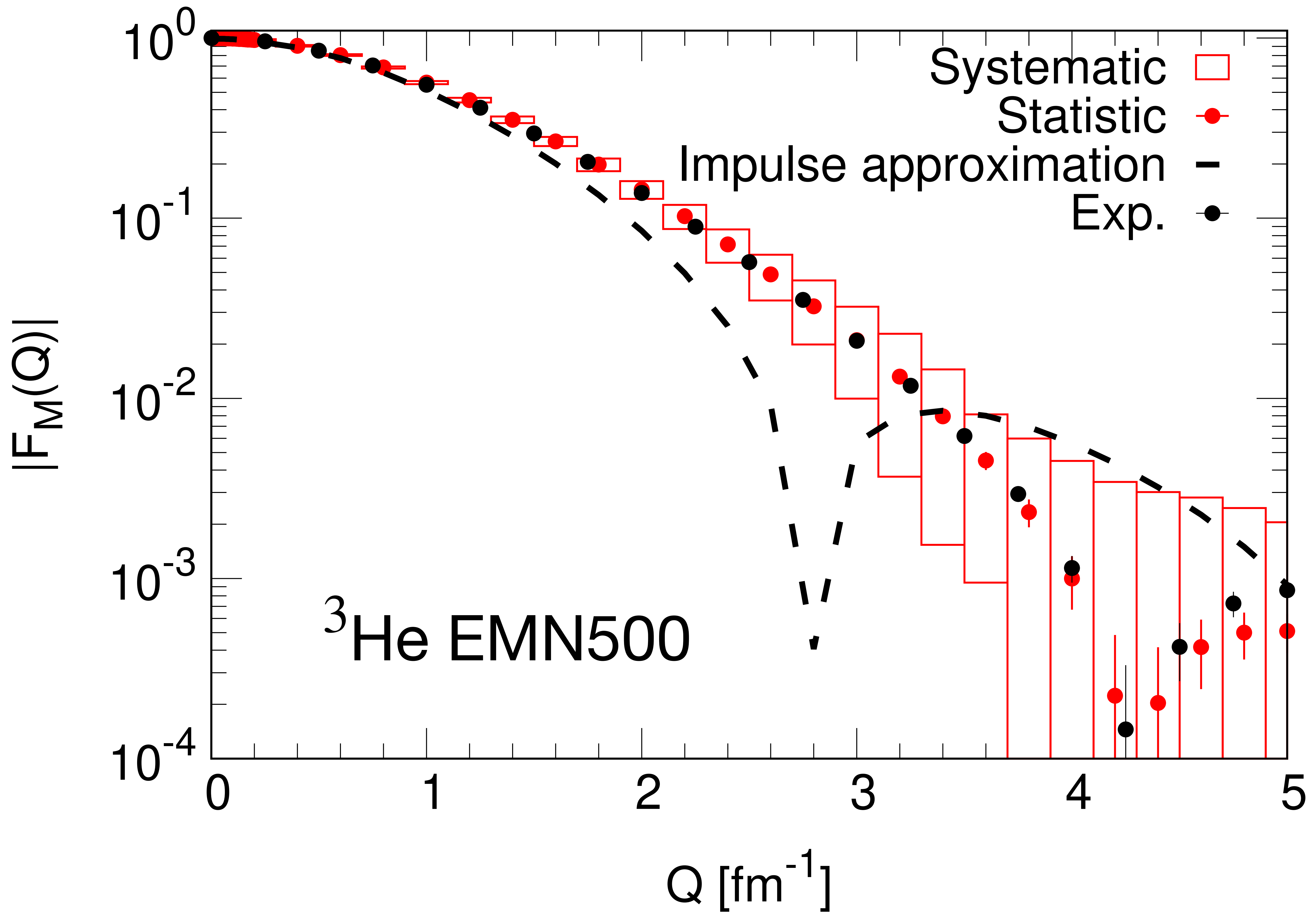
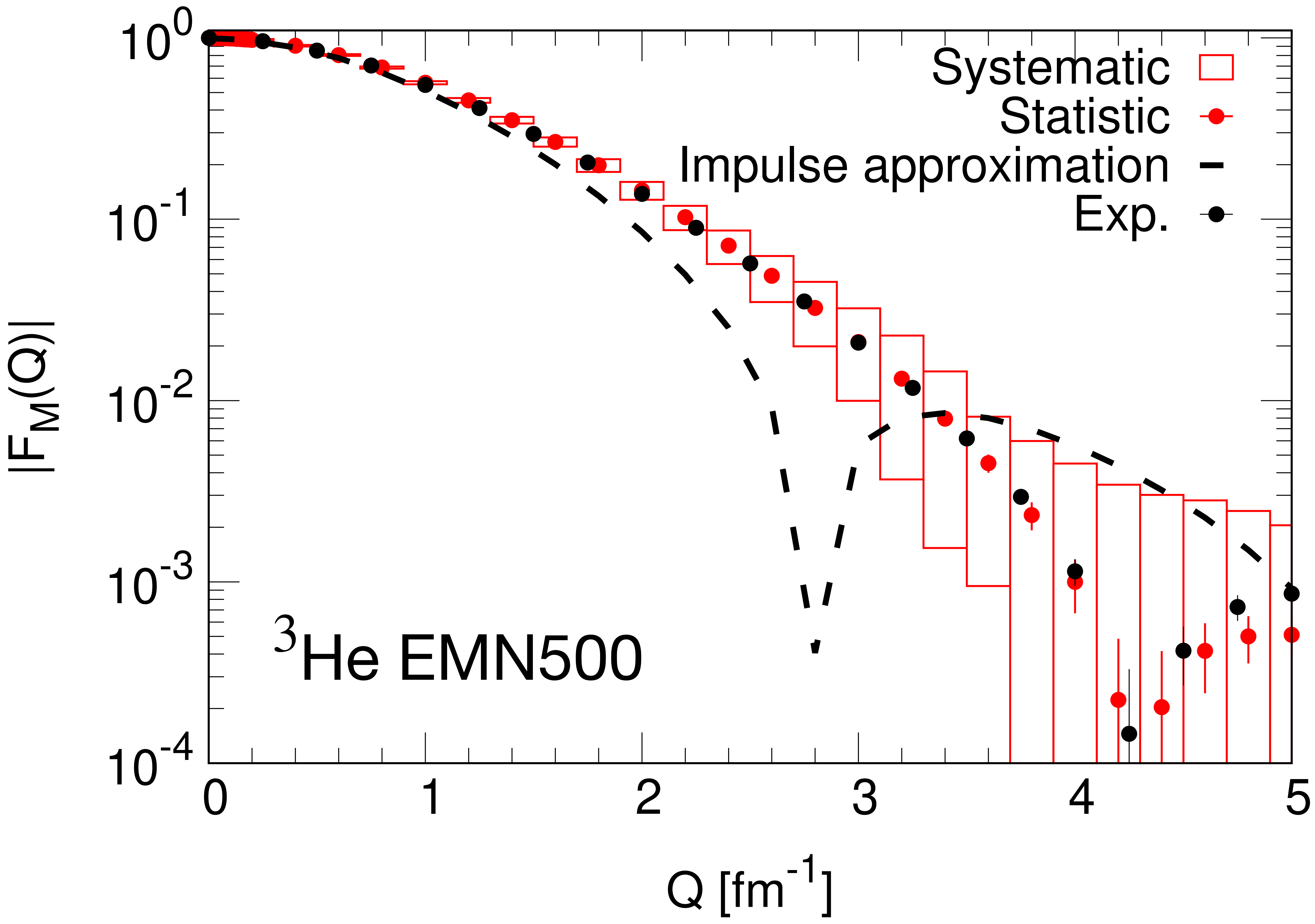
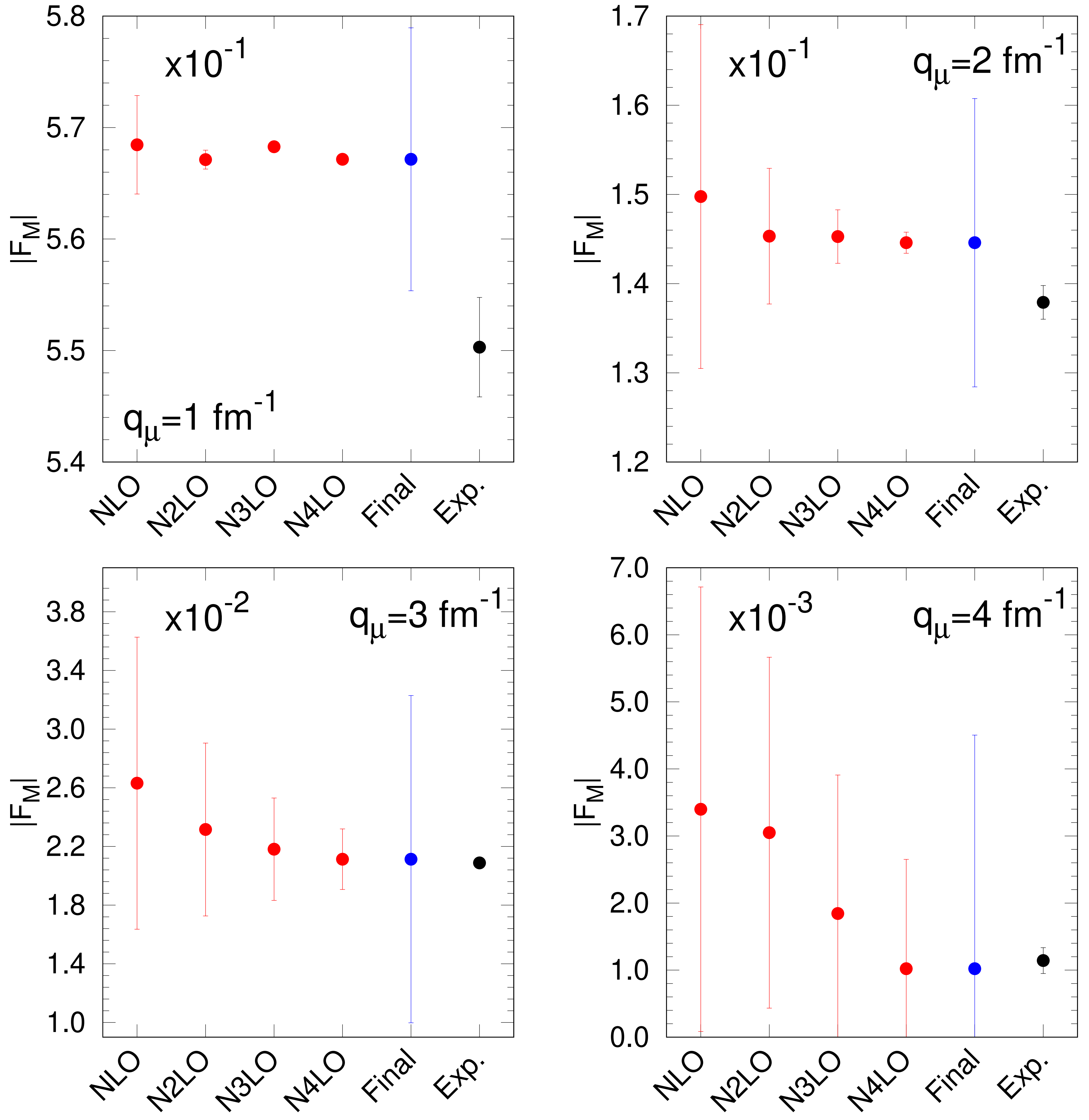


Error estimate

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

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





Mirror nuclei structure

The reason

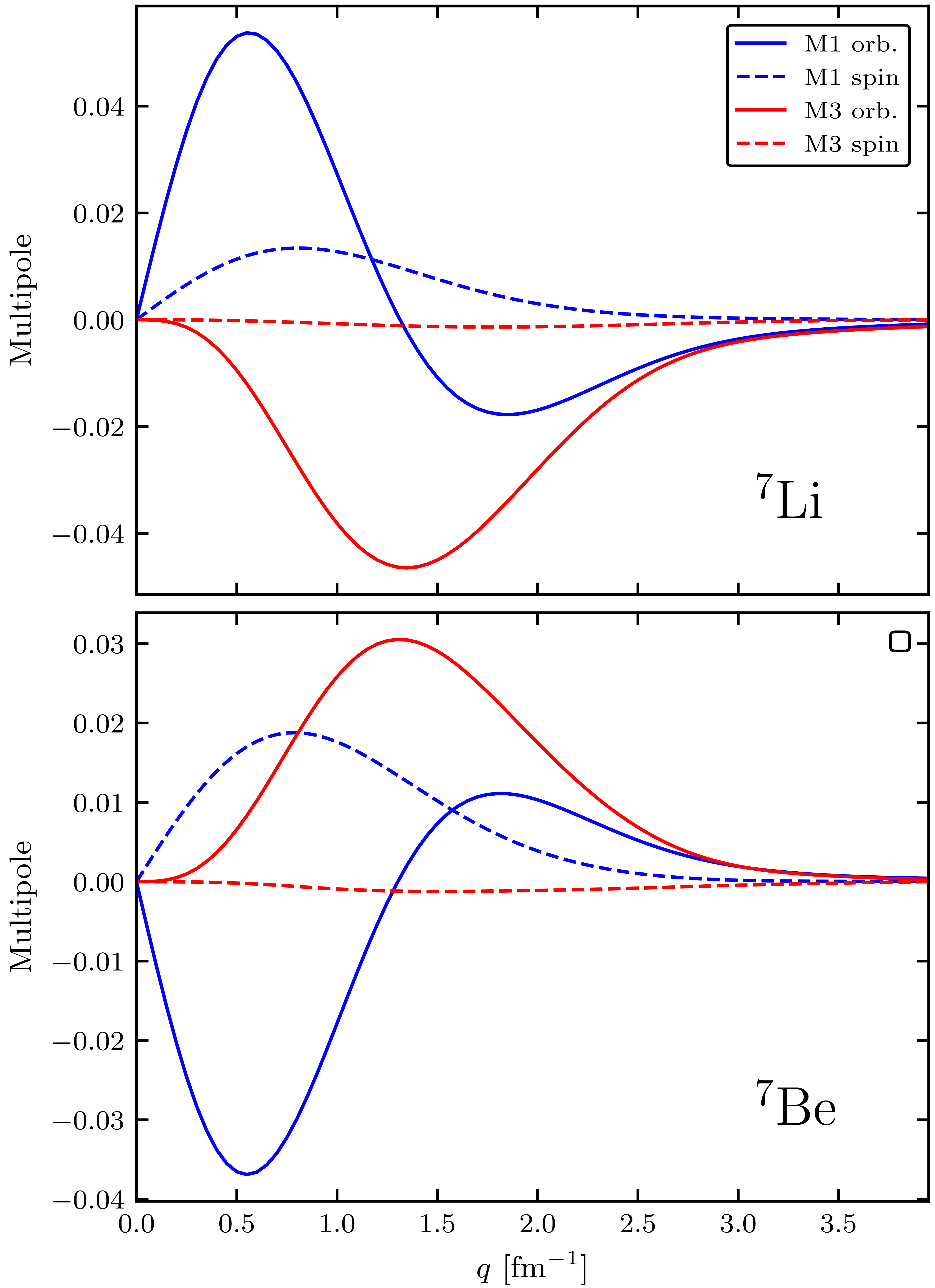
$$\mathbf{j}^{\mathrm{LO}}(\mathbf{q}) = \frac{\epsilon_i(q_\mu^2)}{2\,m}\,\left[\mathbf{p}_i\,,\,\mathrm{e}^{i\mathbf{q}\cdot\mathbf{r}_i}\right]_+ + i\,\frac{\mu_i(q_\mu^2)}{2\,m}\,\mathrm{e}^{i\mathbf{q}\cdot\mathbf{r}_i}\,\sigma_i\times\mathbf{q}\,,$$

Convection current

Magnetic current

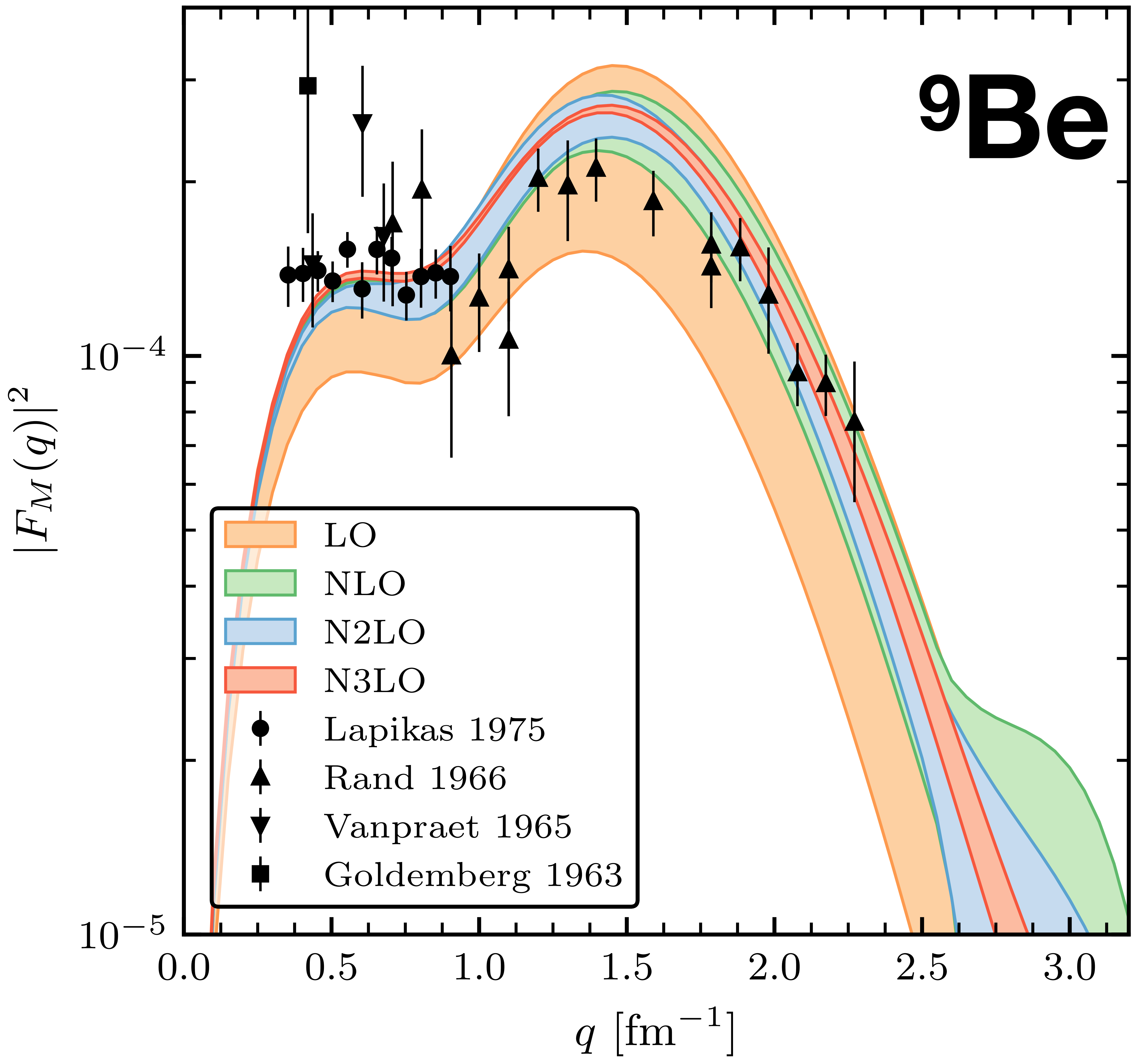
No contribution to M_3

Change sign if there is an unpaired neutron/proton



Order by order expansion

- Error analysis based on: [EPJA 51, 53 (2015)]
- Expansion parameter: $Q = (A-1)/A \times q/\Lambda_b,\ \Lambda_b = 700\,\mathrm{MeV}$
- Chiral expansion seems to have in general a good behavior.
- N3LO corrections for some nuclei are of the same size of N2LO.



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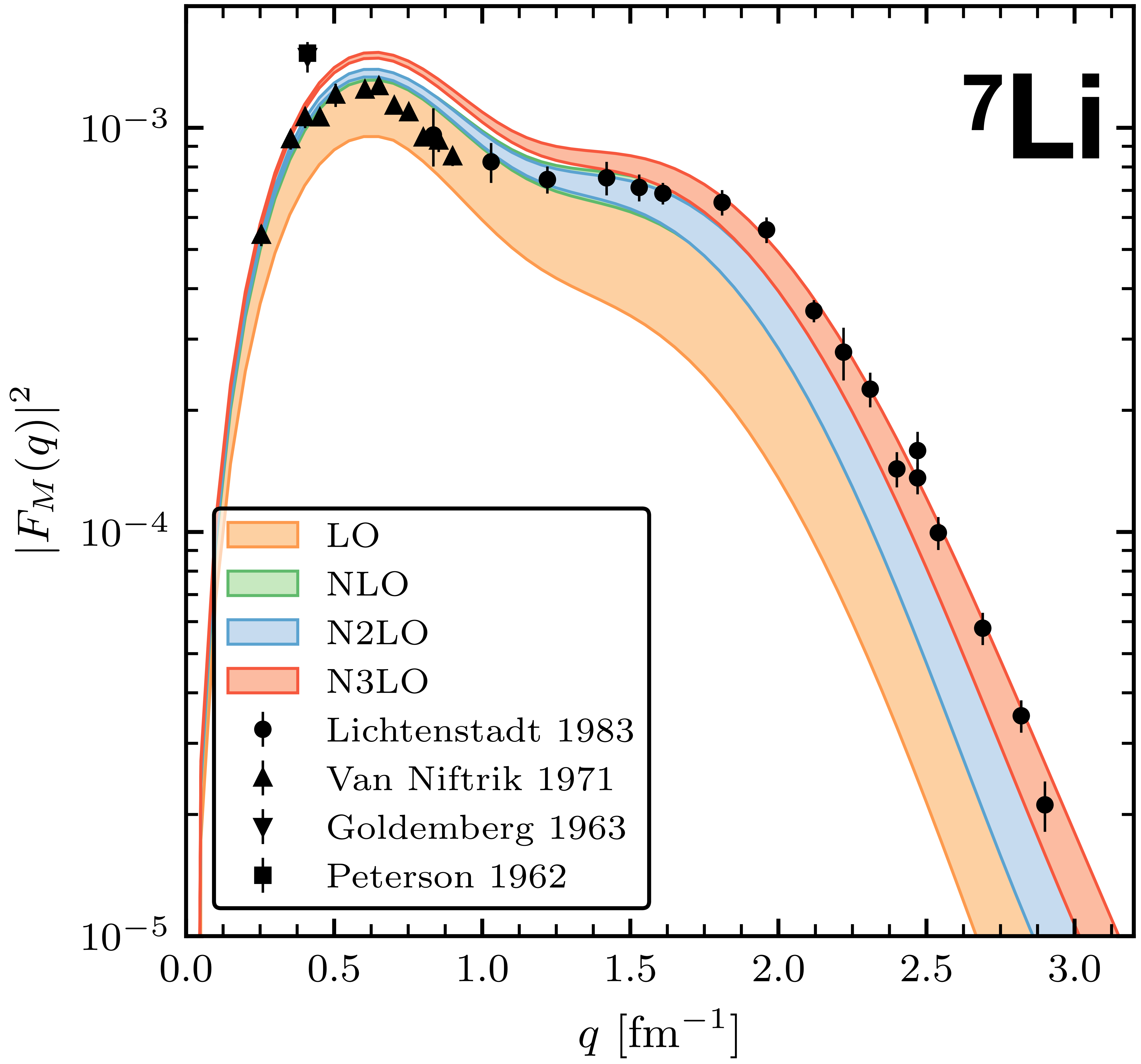
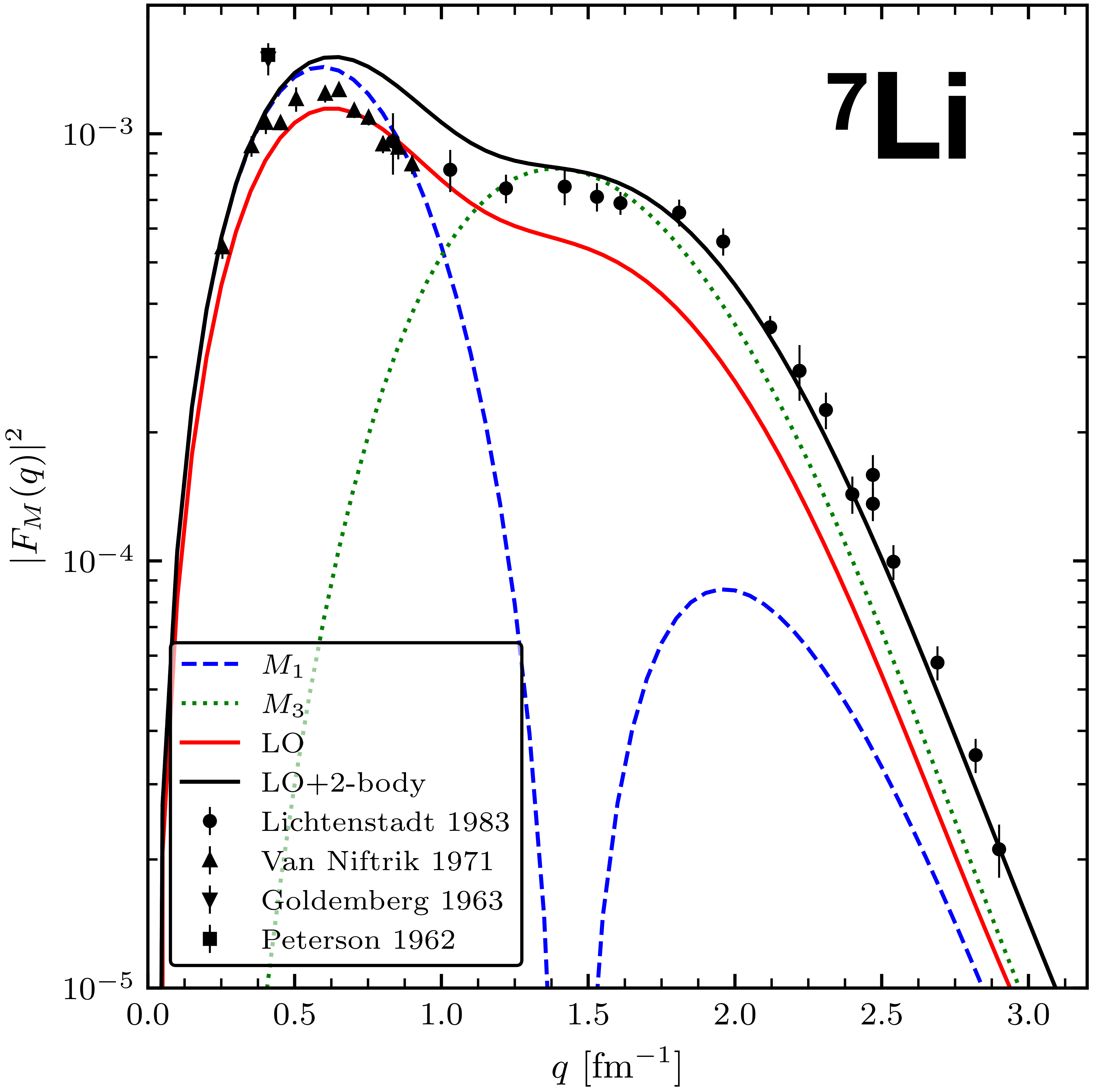
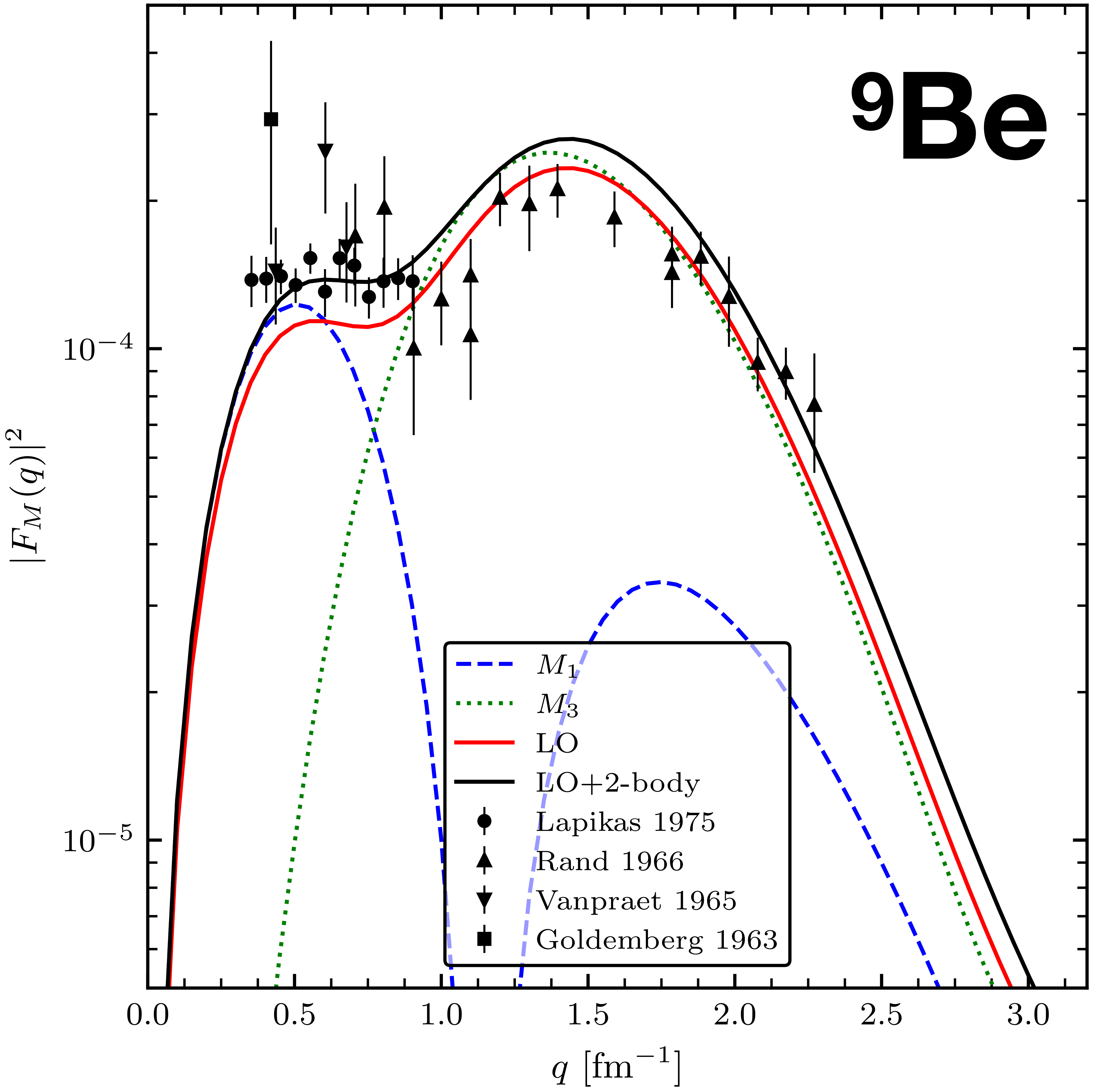


Magnetic form factor predictions

Lithium-7 and Berilium-9 (isovector dominated)





Magnetic form factor predictions

Lithium-6 and Boron-10 (isoscalar transition)