Quantum Monte Carlo Calculations of Magnetic Moments for $A \leq 10$ Nuclei

MAYORANA Summer School
Modica, Italy

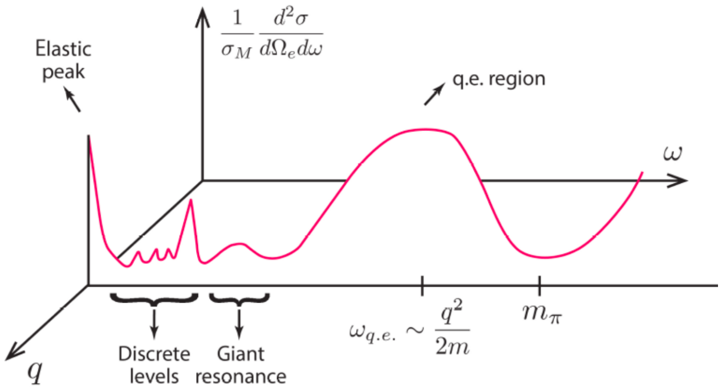
Graham Chambers-Wall
July 6, 2023

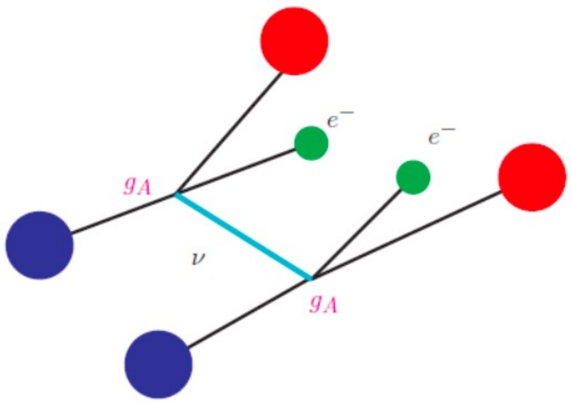
Advisors: Saori Pastore and Maria Piarulli

Collaborators: Garrett King and Alex Gnech

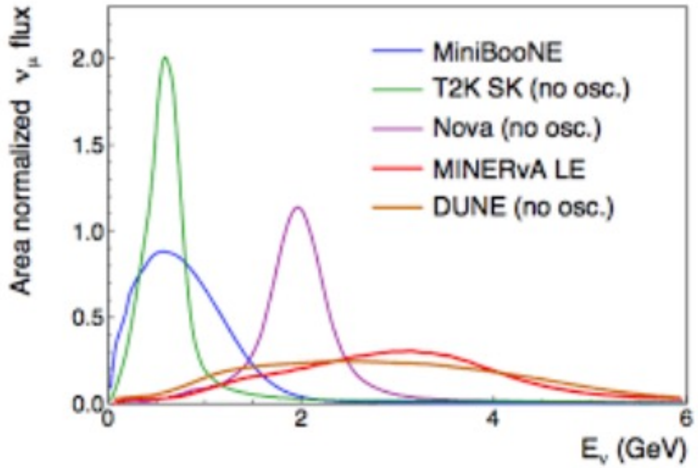
Motivation

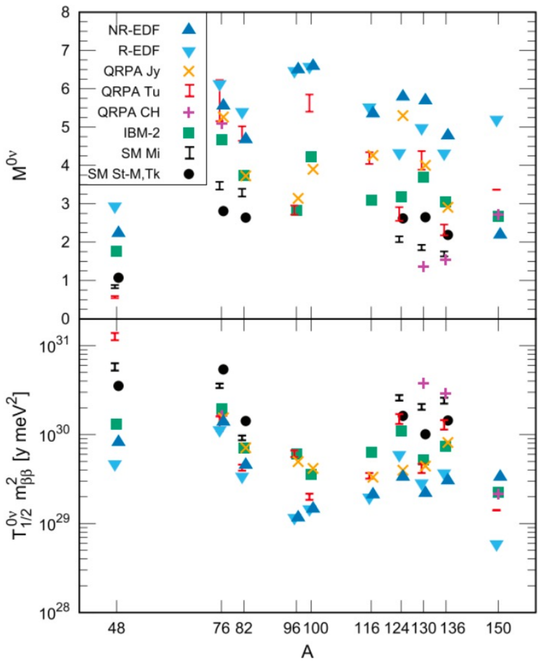
$$\Gamma_{0\nu} \propto (\mathrm{NME})^2 \times \langle m_{\beta\beta} \rangle^2$$





Electroweak phenomena important in searches for new physics across range of kinematics





Engel and Menéndez Rep. Prog. Phys. 80 046301 (2017)

Quantum Monte Carlo Methods

- Want to solve many-nucleon Schrödinger equation: $H\Psi(J^\pi;T,T_z) = E\Psi(J^\pi;T,T_z)$

- Determine wavefunction through variational principle by minimizing the expectation value

$$E_V = \frac{\langle \Psi_V | H | \Psi_V \rangle}{\langle \Psi_V | \Psi_V \rangle} \geq E_0$$

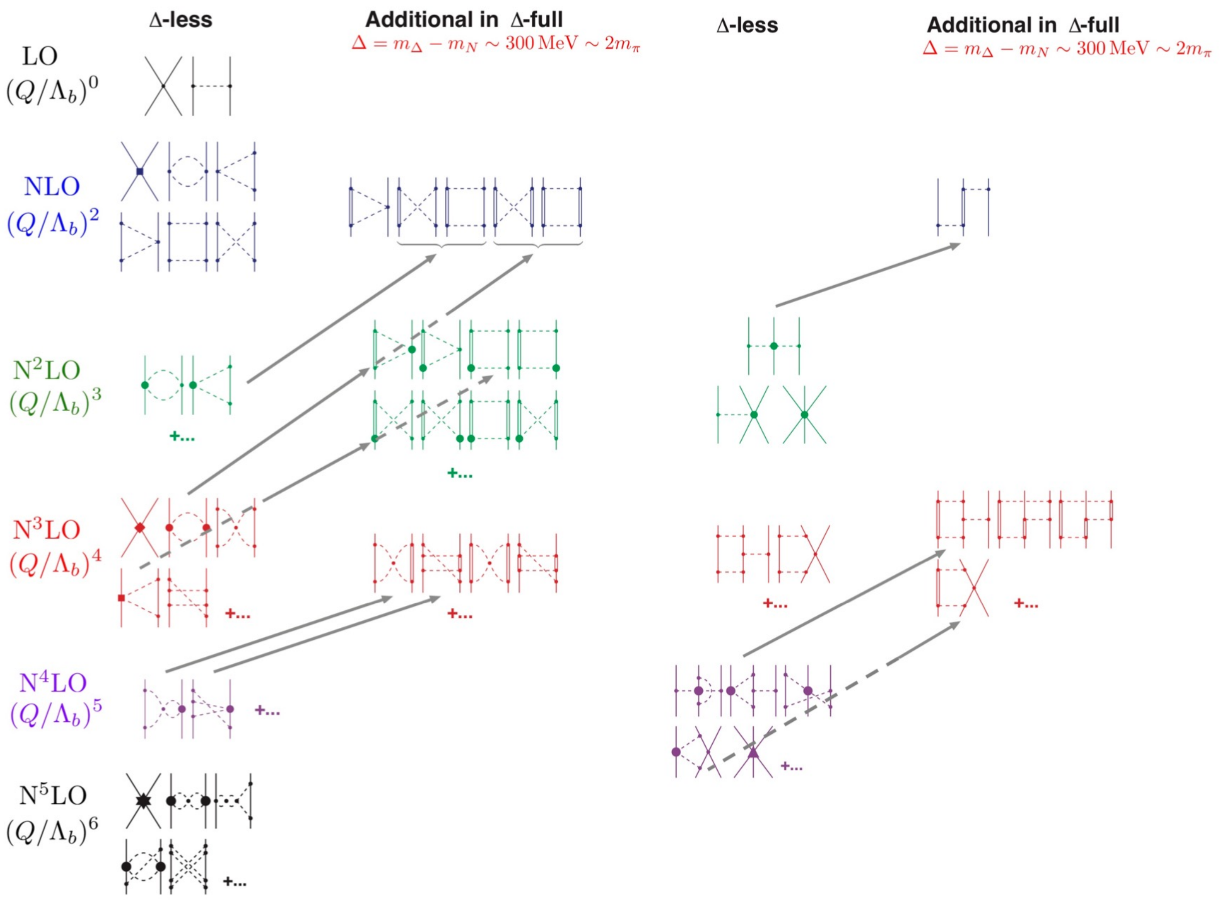
- The trial wavefunction is

$$|\Psi_V\rangle = \mathcal{S}\prod_{i<j}\left[1 + U_{ij} + \sum_{i<j\neq k} \tilde{U}^{TNI}_{ijk}\right]|\Psi_J\rangle$$

- Variational parameters encoded in correlation operators U_{ij} and $\tilde{U}^{TNI}_{ijk}$

Carlson et al. Rev. Mod. Phys. ***87****, 1067*

Many-body Interactions with Chiral Effective Field Theory



Piarulli and Tews, Front. Phys. ***30*** *(2020)*

- Chiral Effective Field Theory (χEFT)
  - EFT with same symmetries of QCD below chiral symmetry breaking scale ~ 1 GeV
- Degrees of freedom are nucleons, pions, and Δ(1232)
- Long- and intermediate-range interactions through pion exchange
- Short-range interactions through contact terms with low-energy constants (LECs)

Norfolk (NV2+3) Interactions

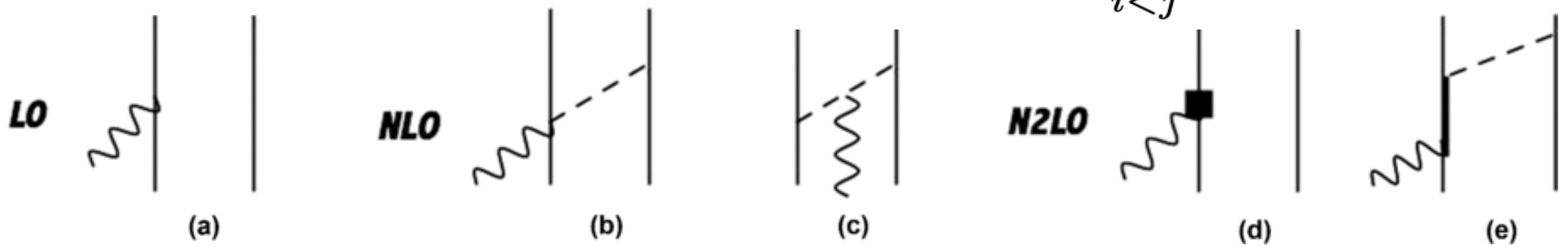
$$H = \sum K_i + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk}$$

Compare two different models (Ia* & IIb*) which use different data and regulators

Ia* (IIb*) fit to *NN* scattering data up to 125 (200) MeV and uses a soft (hard) cutoff

Both have three-body terms constrained to weak and strong data

Need many-nucleon electromagnetic current: $\mathbf{j} = \sum \mathbf{j}_i + \sum_{i<j} \mathbf{j}_{ij} + \cdots$



S. Pastore et al., Phys. Rev. C ***80****, 034004 (2009)* *R. Schiavilla et al., Phys. Rev. C* ***99****, 034005 (2019)*

Magnetic Form Factor

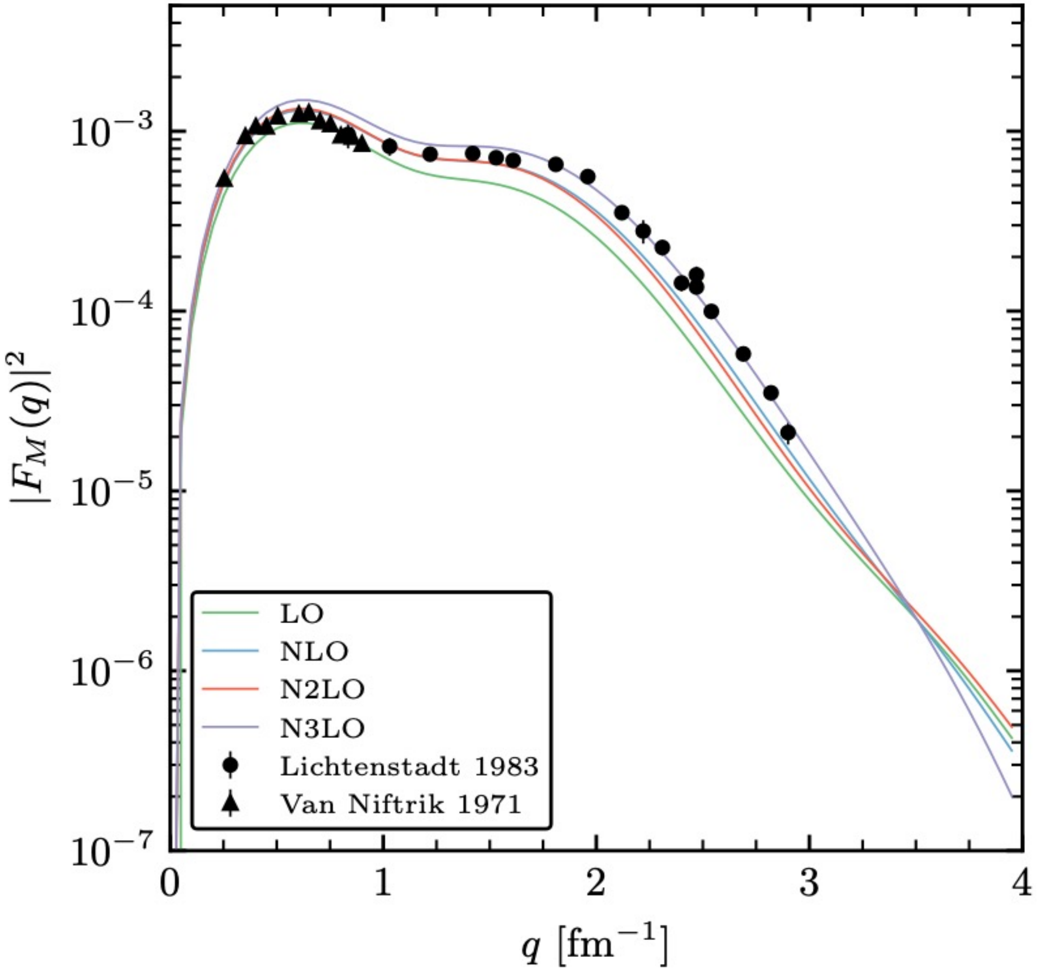
- Magnetic form factor expressed in expansion of magnetic multipole operators:

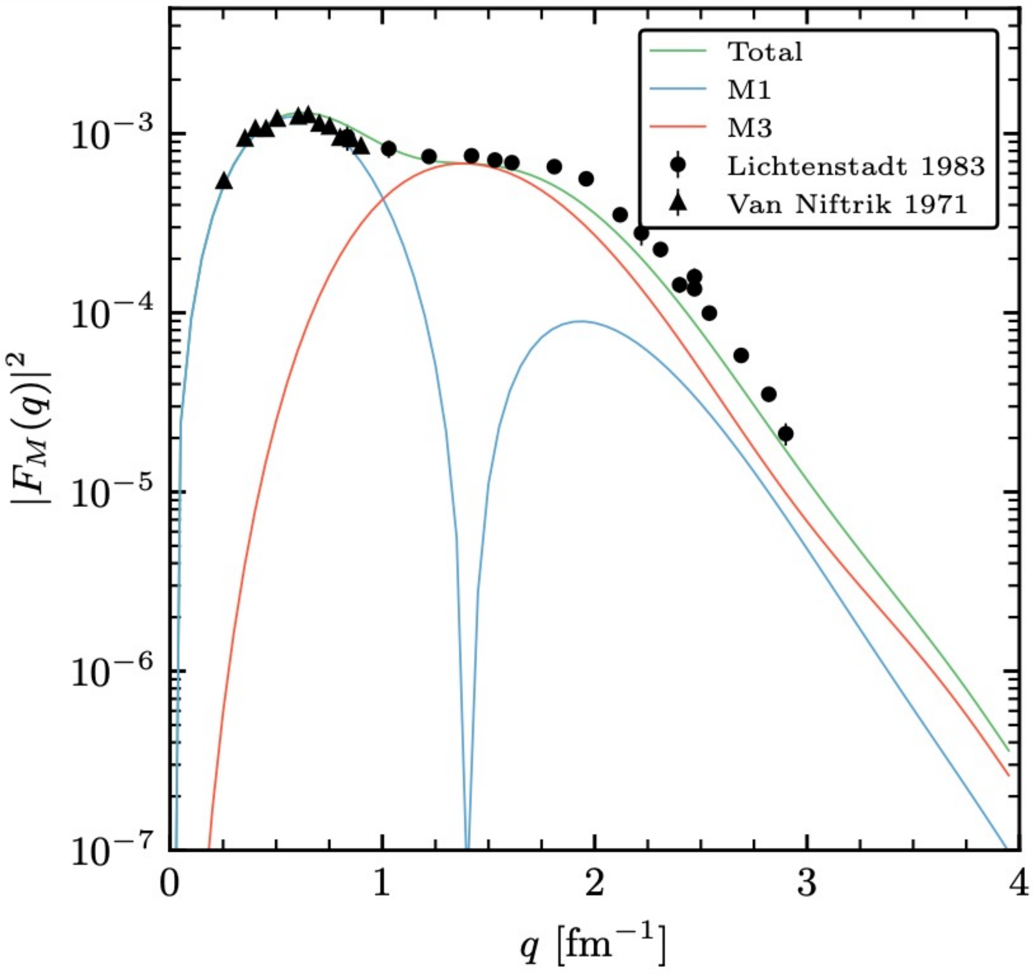
$$F_M^2(q) = \frac{1}{2J_i + 1} \sum_{L=0}^{\infty} |\langle J_f || M_L || J_i \rangle|^2$$

- Reduced matrix elements extracted from evaluating matrix element of electromagnetic current operator $\mathbf{j}_\gamma(\mathbf{q})$

- In practice, select matrix element of $\mathbf{j}_\gamma(\mathbf{q})$ in specific state $M_J = J$ and change direction of $\hat{\mathbf{q}}$ to isolate magnetic multipole contributions

^{7}Li Magnetic Form Factor





^{7}Li magnetic form factor as a function of q for different orders in the expansion (left) and with different magnetic multipole contributions (right). Figures and calculations created in collaboration with Garrett King and Alex Gnech.

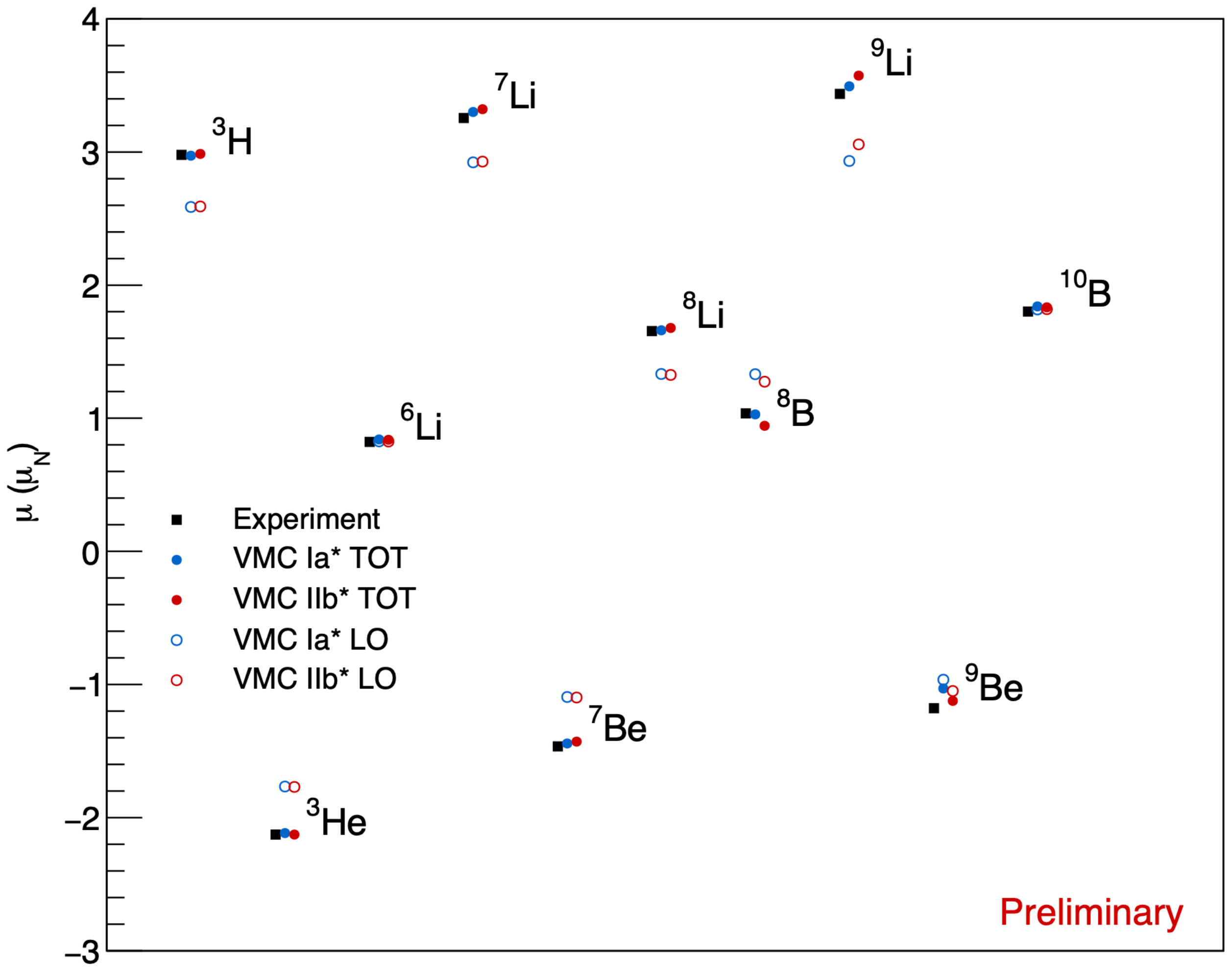
Magnetic Moments

Magnetic moment is small q limit of the magnetic form factor:

$$\mu = \lim_{q \to 0} F_M(q)$$

Calculations with all contributions (TOT) have good agreement with data

Small (<5%) differences between the two models



Conclusions

- Up to N3LO needed to match high momentum data in ^{7}Li example
- Reported VMC magnetic moment calculations for $A \leq 10$ nuclei
  - Small differences (<5%) in using Ia* vs IIb*
  - Plan to do same calculations for additional nuclei (^{9}C, $A = 11$)
- Improve results using Green's Function Monte Carlo (GFMC)

Acknowledgments

Thank you!

In collaboration with Garrett King, Alex Gnech, Maria Piarulli, and Saori Pastore

This material is based upon work supported by the NSF Graduate Research Fellowship Program under grant No. DGE 2139839 and the DOE under contract No. DE-SC0021027.