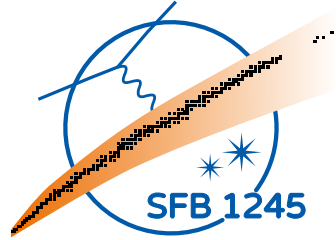




LOEWE

Exzellente Forschung für
Hessens Zukunft



TECHNISCHE
UNIVERSITÄT
DARMSTADT

NUCLEAR RESPONSES FOR MUON CAPTURE AND RARE DECAYS

Lotta Jokiniemi (she/her)

Institut für Kernphysik, Theoriezentrum, TU Darmstadt

MITP Workshop “*Many-Body Theory: Nuclear Physics Meets Quantum Chemistry*”,
Mainz, August 24 – September 4, 2026

COLLABORATORS



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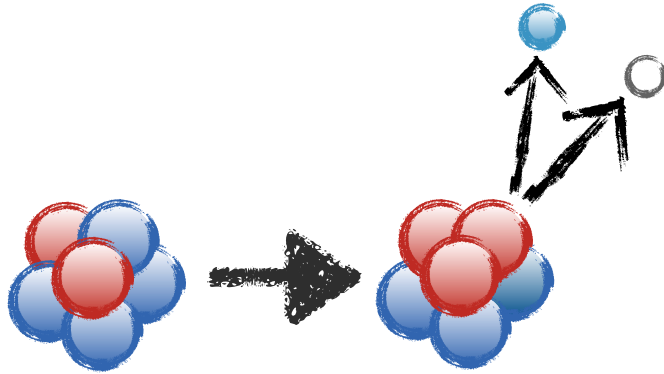


THE UNIVERSITY
of NORTH CAROLINA
at CHAPEL HILL

B. Romeo

DOUBLE-BETA DECAY

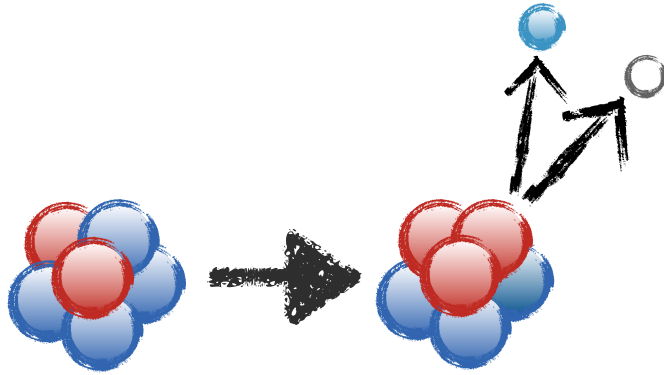
Beta (β^-) decay



*One of the most common
decays*

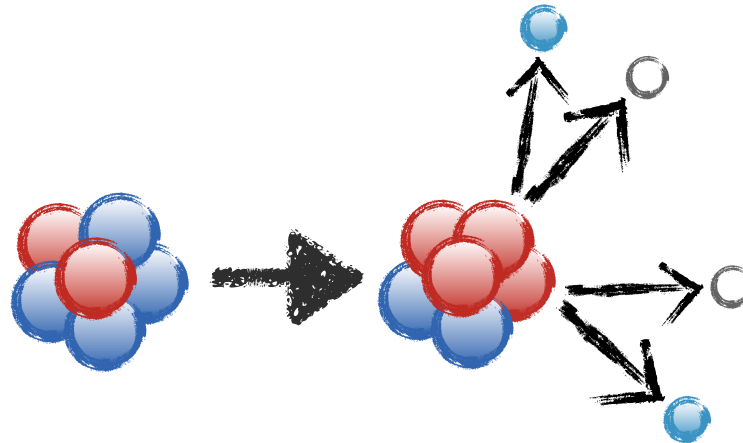
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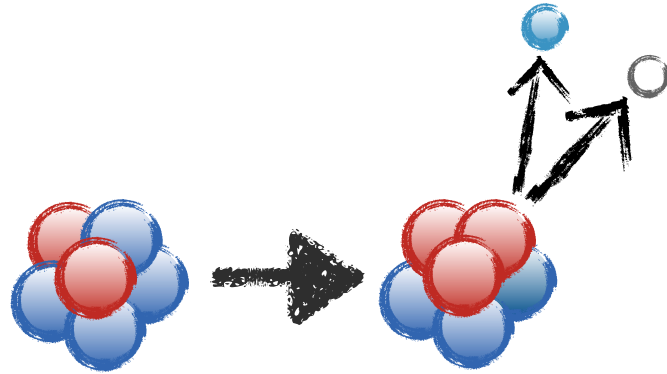
Two-neutrino double- β
($2\nu\beta\beta$) decay



Rarest measured decay

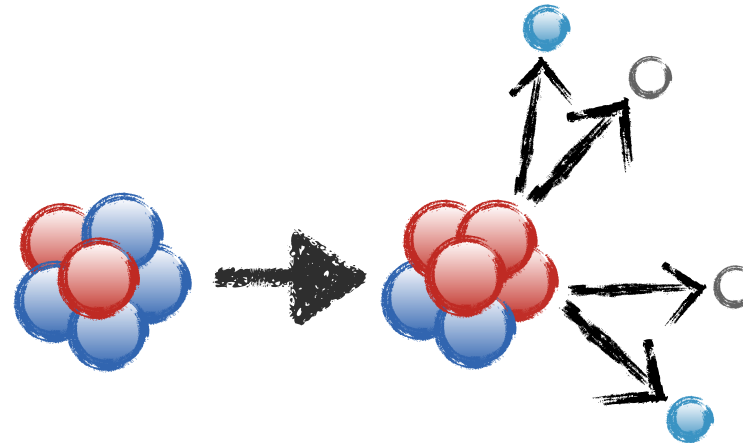
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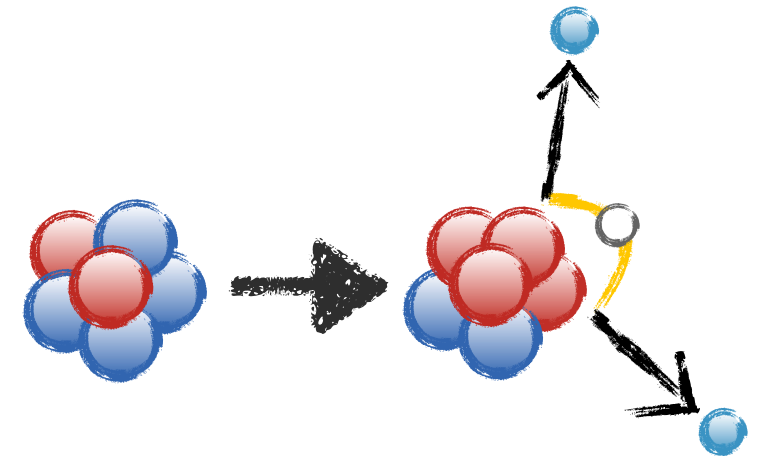
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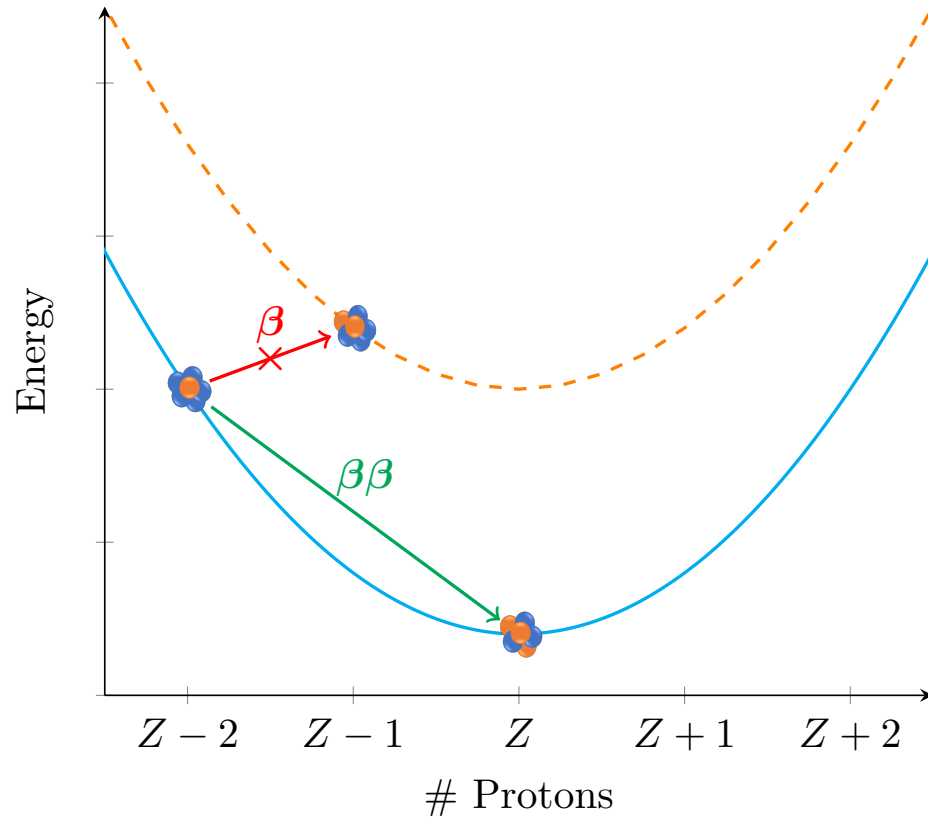
Rarest measured decay

Neutrinoless double- β
($0\nu\beta\beta$) decay

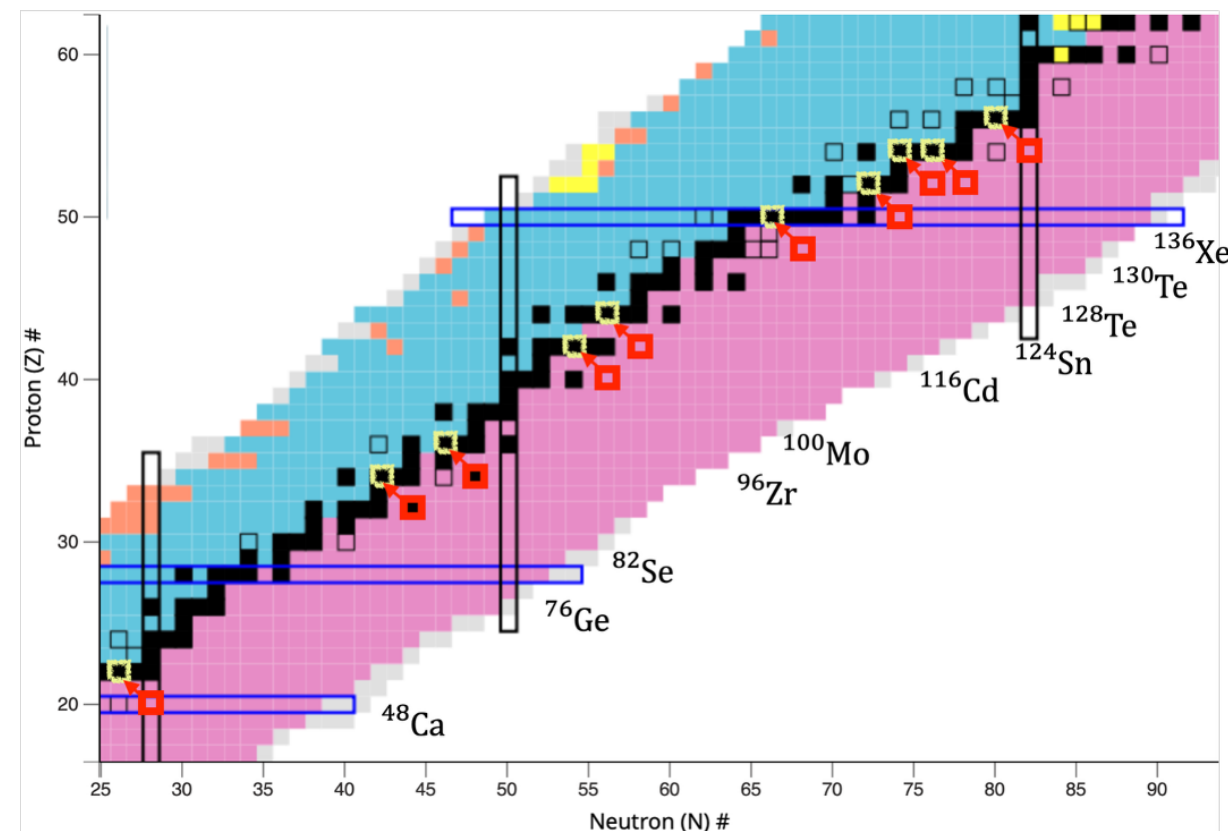
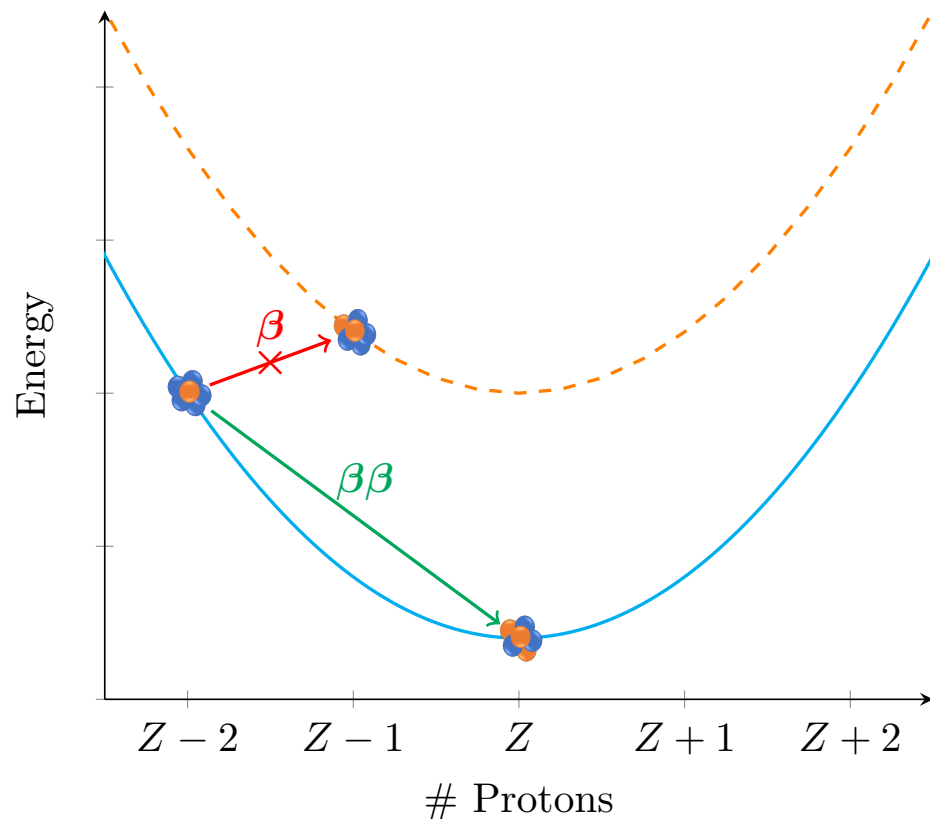


Not yet observed

DOUBLE-BETA-DECAY CANDIDATES



DOUBLE-BETA-DECAY CANDIDATES

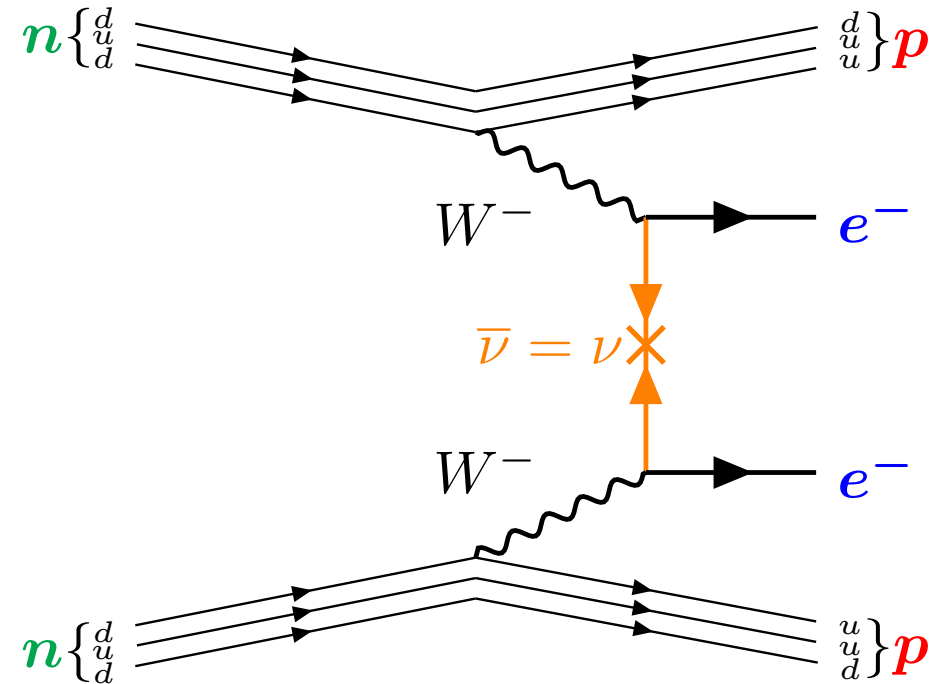


Modified from nndc.bnl.gov/nudat3/



NEUTRINOLESS DOUBLE-BETA ($0\nu\beta\beta$) DECAY

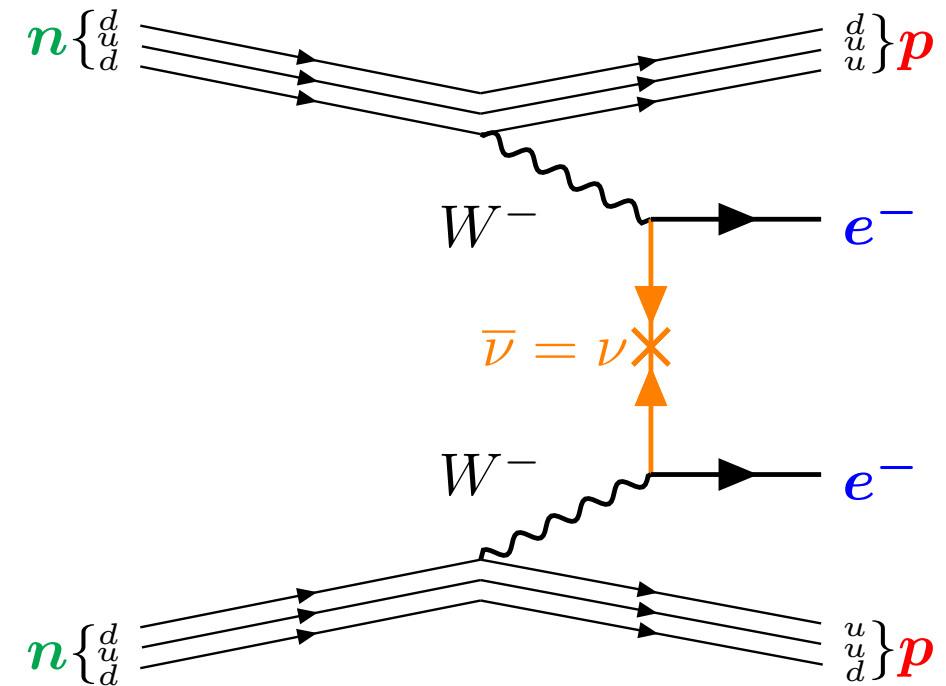
$$(A, Z) \rightarrow (A, Z + 2) + 2e^- + \cancel{2\nu_e}$$



NEUTRINOLESS DOUBLE-BETA ($0\nu\beta\beta$) DECAY

- Violates lepton-number conservation

$$(A, Z) \rightarrow (A, Z + 2) + 2e^- + \cancel{2\nu_e}$$



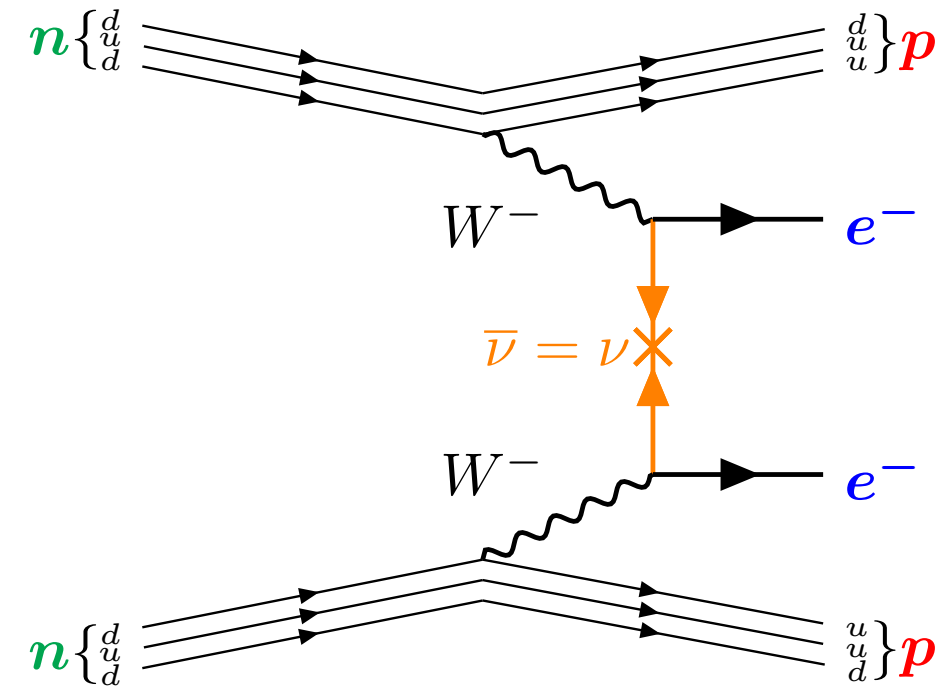


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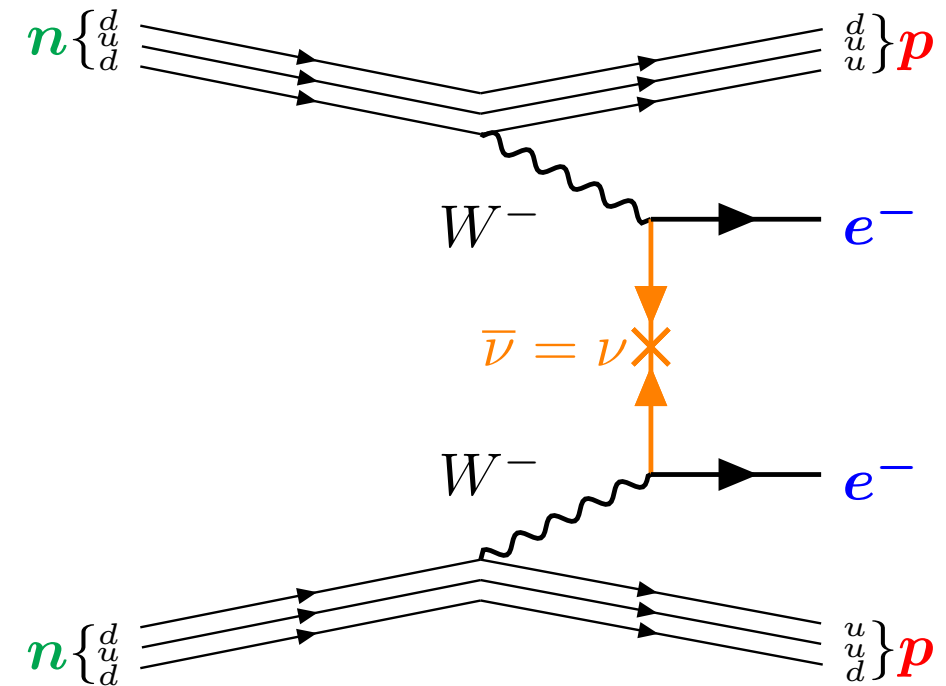


NEUTRINOLESS DOUBLE-BETA ($0\nu\beta\beta$) DECAY

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- Requires that neutrinos are Majorana particles

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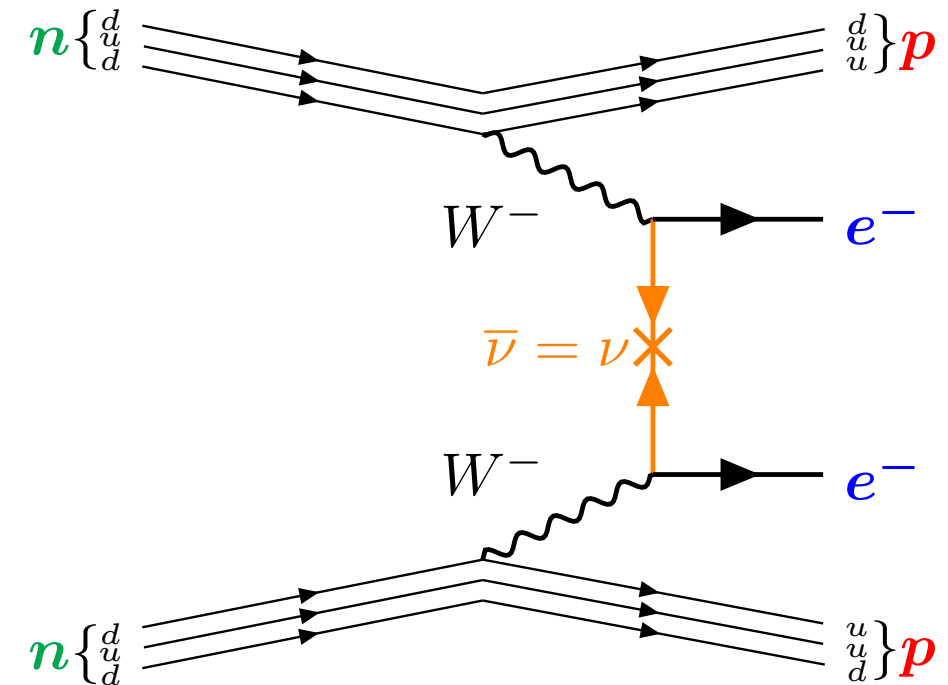


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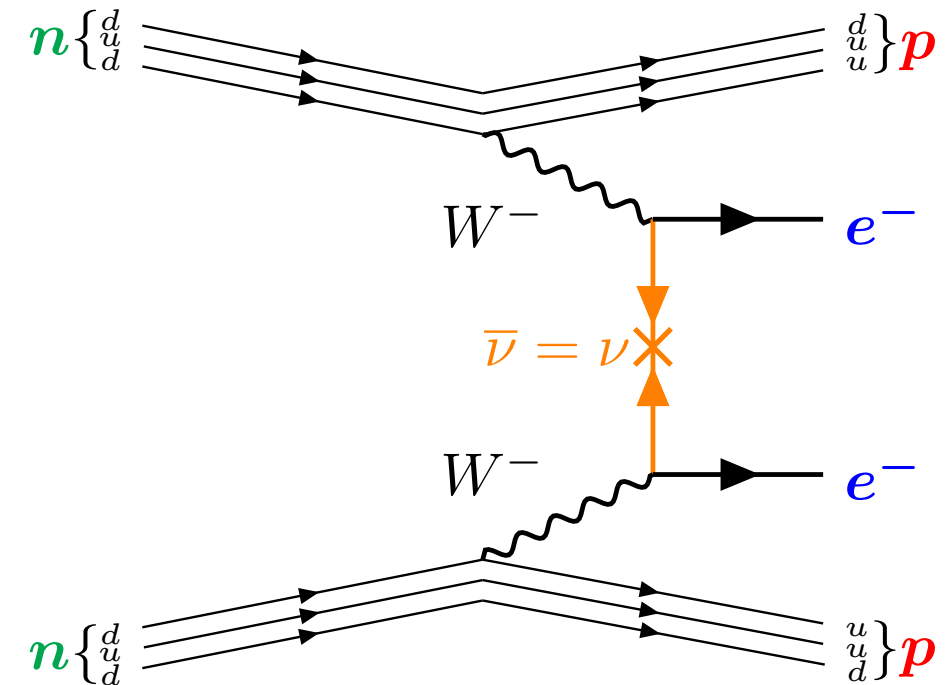
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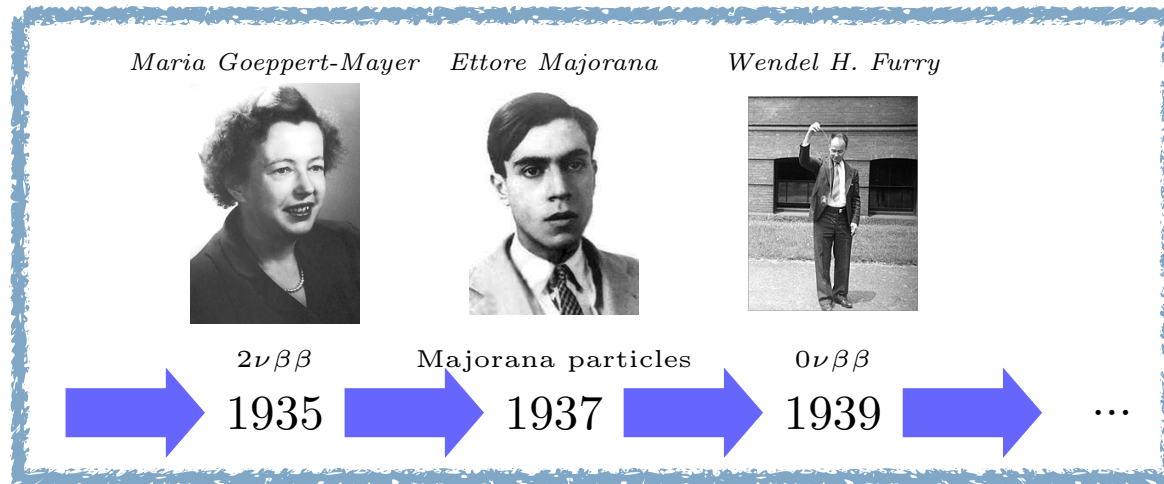
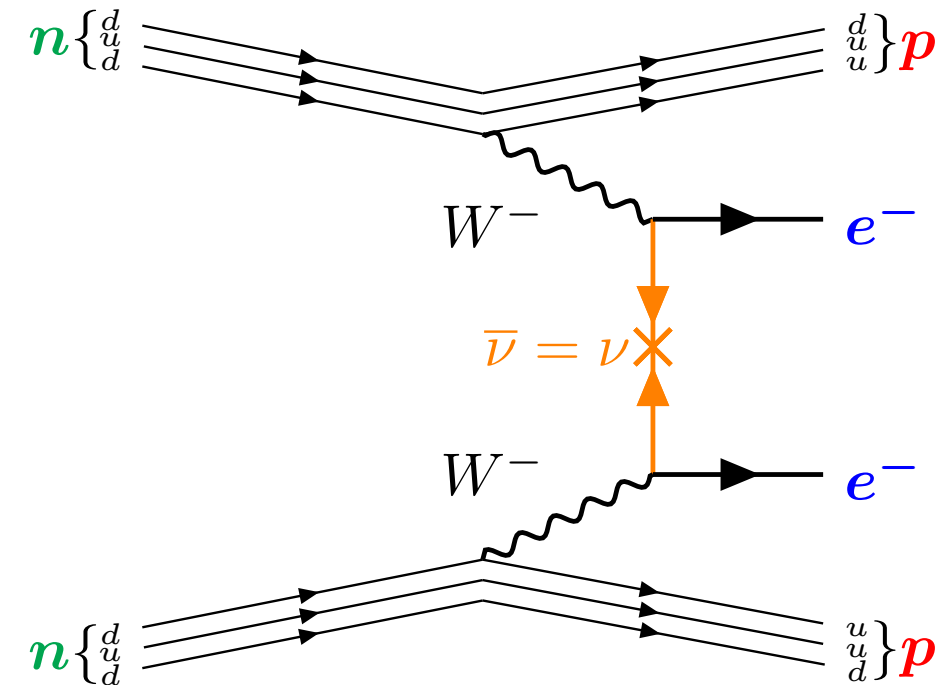


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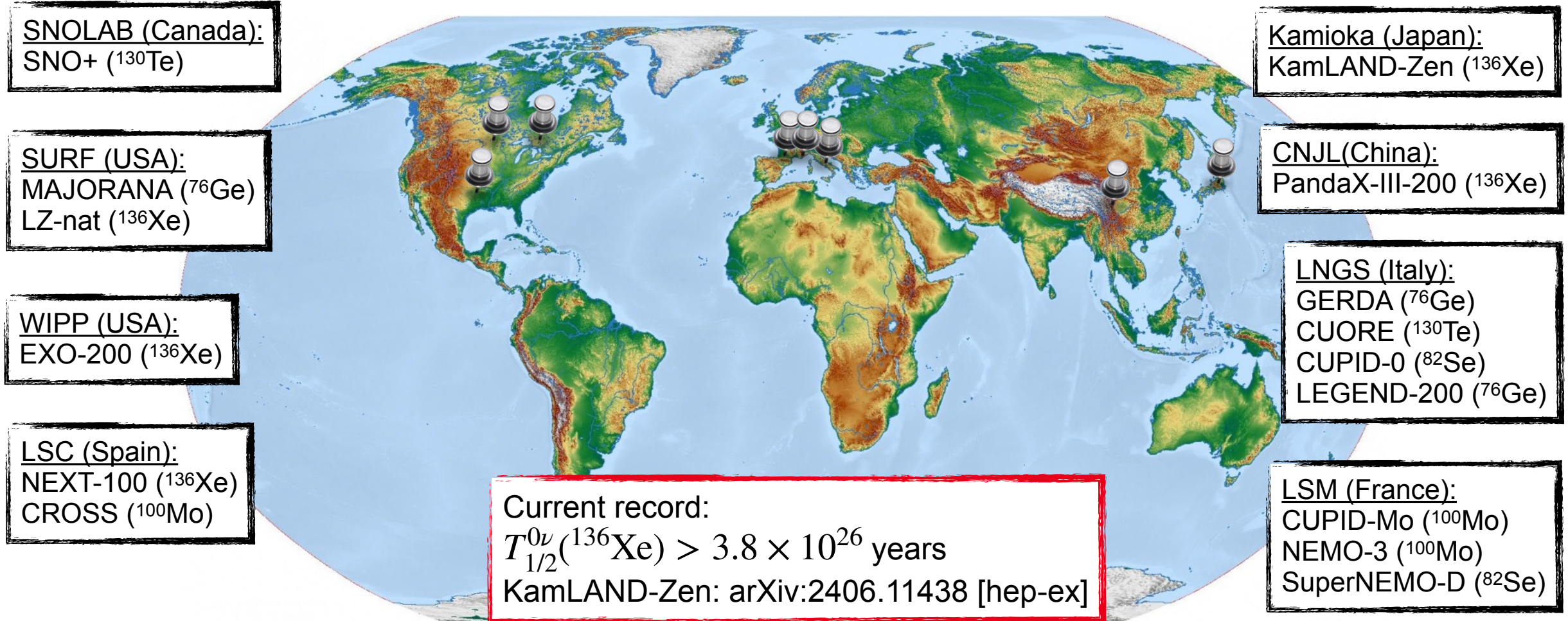
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DOUBLE-BETA-DECAY EXPERIMENTS



$0\nu\beta\beta$ DECAY MEDIATED BY LIGHT-NEUTRINO EXCHANGE

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e} \right)^2$$

$0\nu\beta\beta$ DECAY MEDIATED BY LIGHT-NEUTRINO EXCHANGE

Half-life to be measured

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e} \right)^2$$

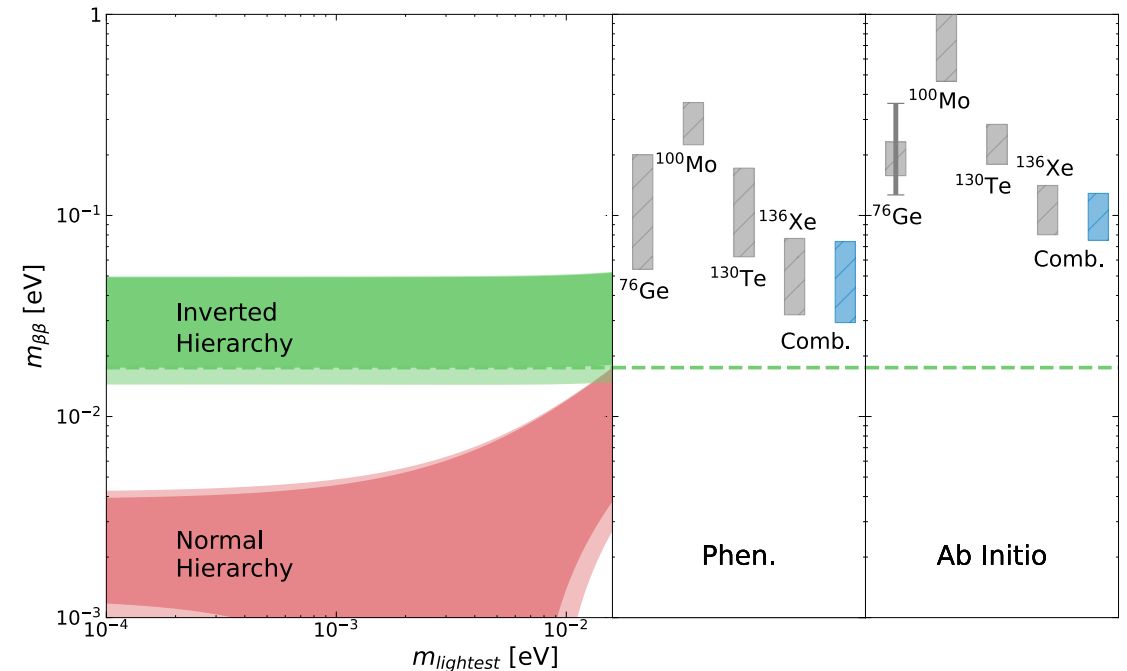
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Majorana mass

$$m_{\beta\beta} = \sum_k (U_{ek})^2 m_k$$



Shickele, Jokiniemi, Belley, Holt, in preparation

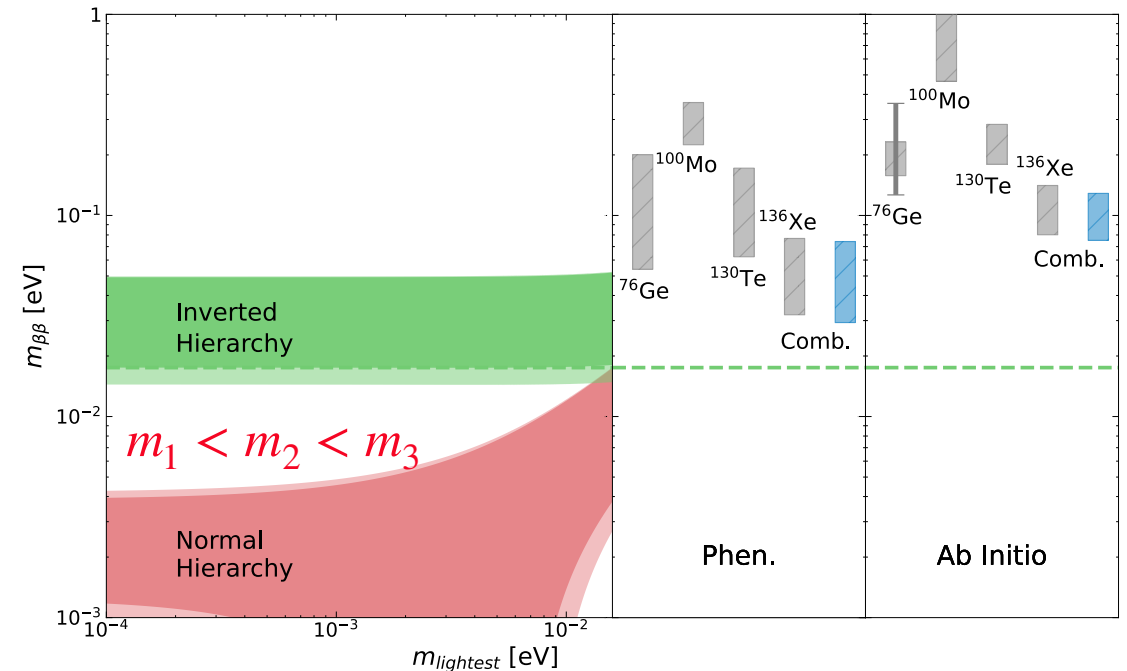
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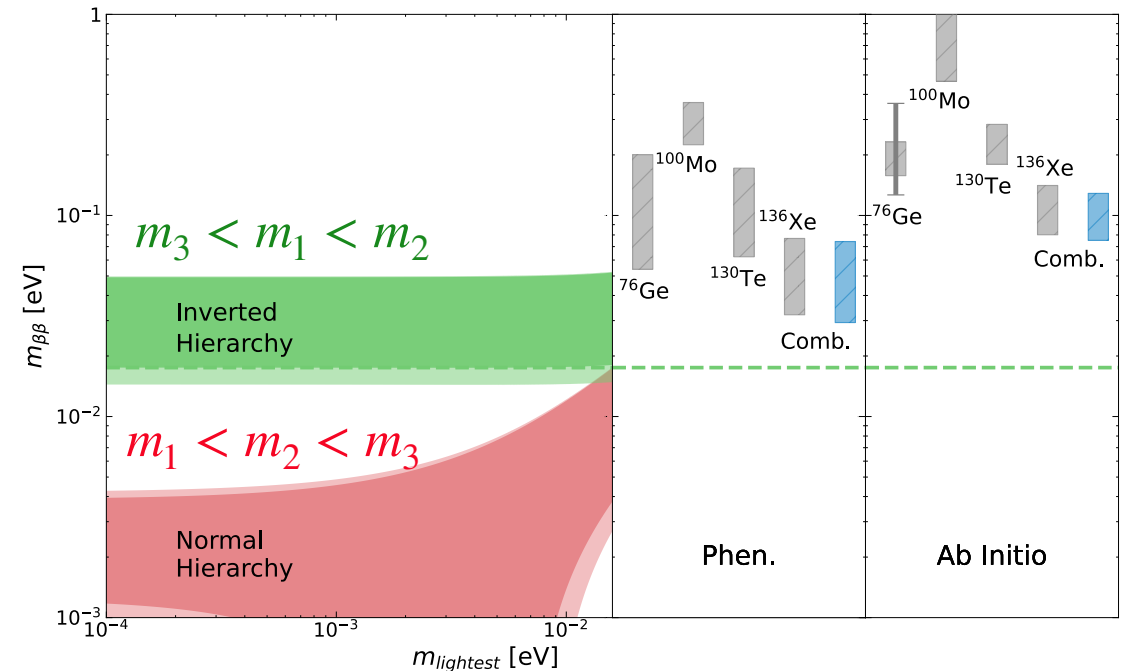
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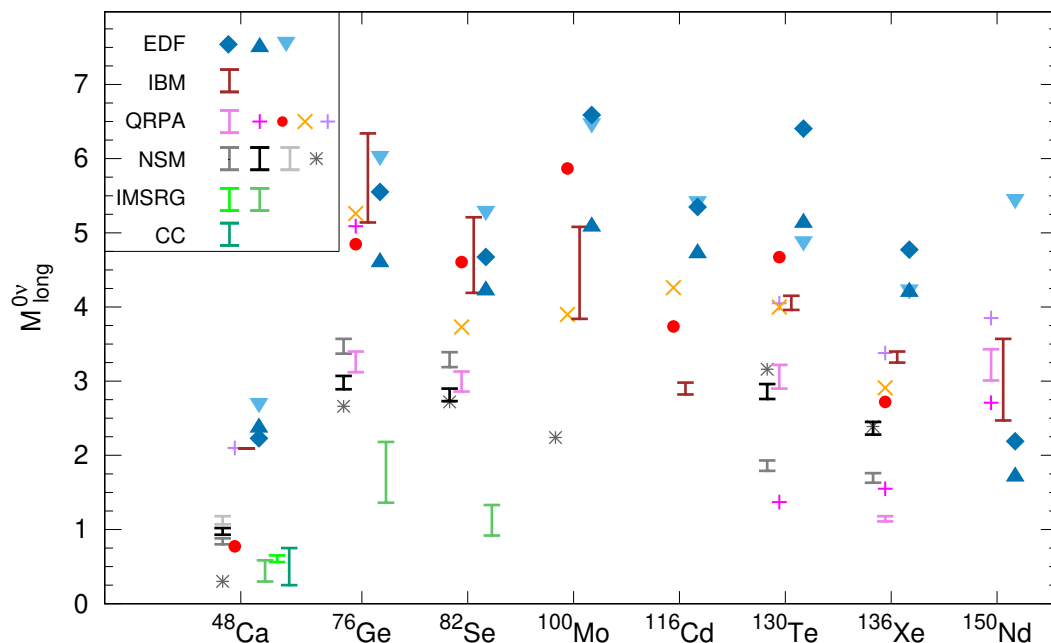
Half-life to be measured

Nuclear matrix element

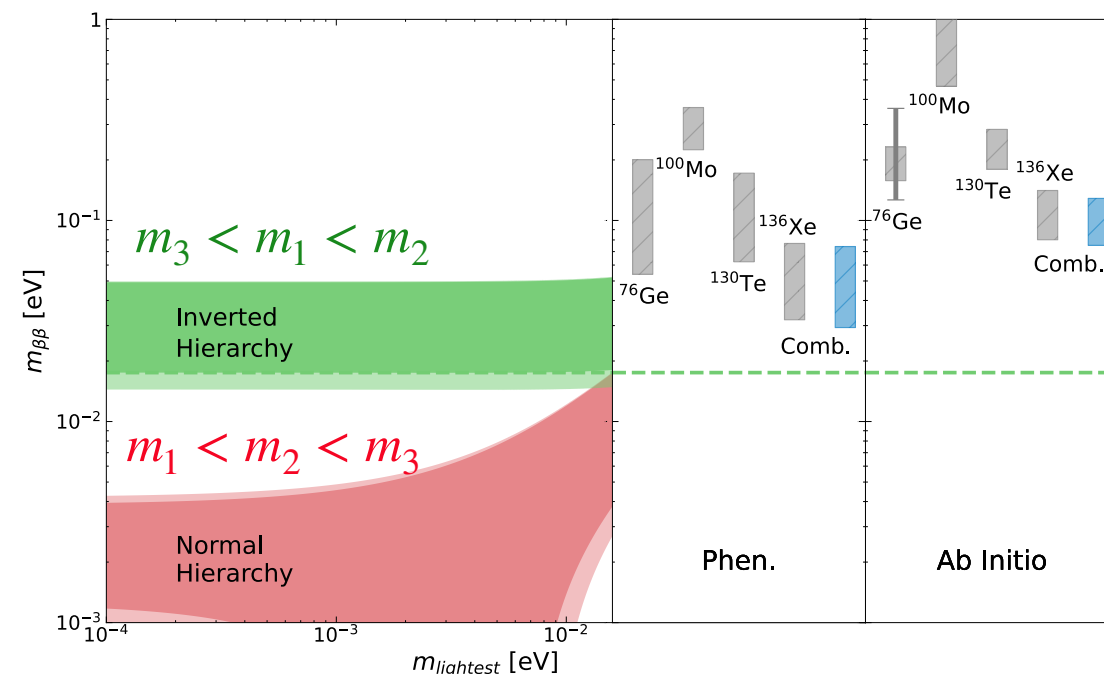
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Agostini et al., Rev. Mod. Phys. 95, 025002 (2023)



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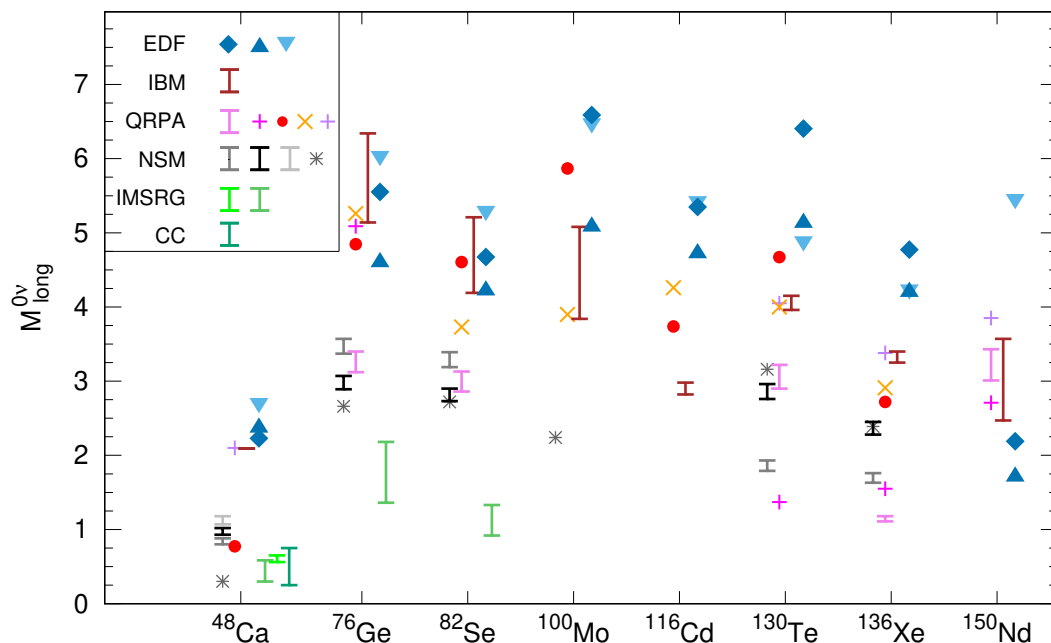
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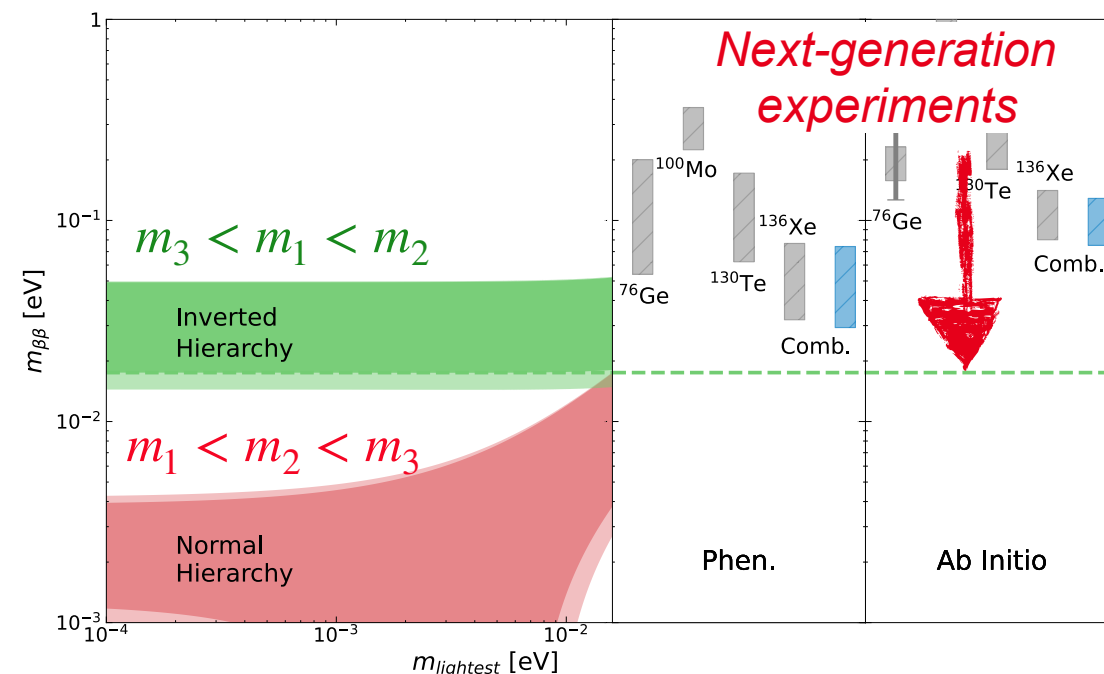
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THE NUCLEAR MATRIX ELEMENT

$$M^{0\nu} = \langle \Psi_f^{(A)} | \mathcal{O}^{0\nu} | \Psi_i^{(A)} \rangle$$

THE NUCLEAR MATRIX ELEMENT

Operator ($nn \rightarrow pp + 2e^-$)



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Initial state wave function

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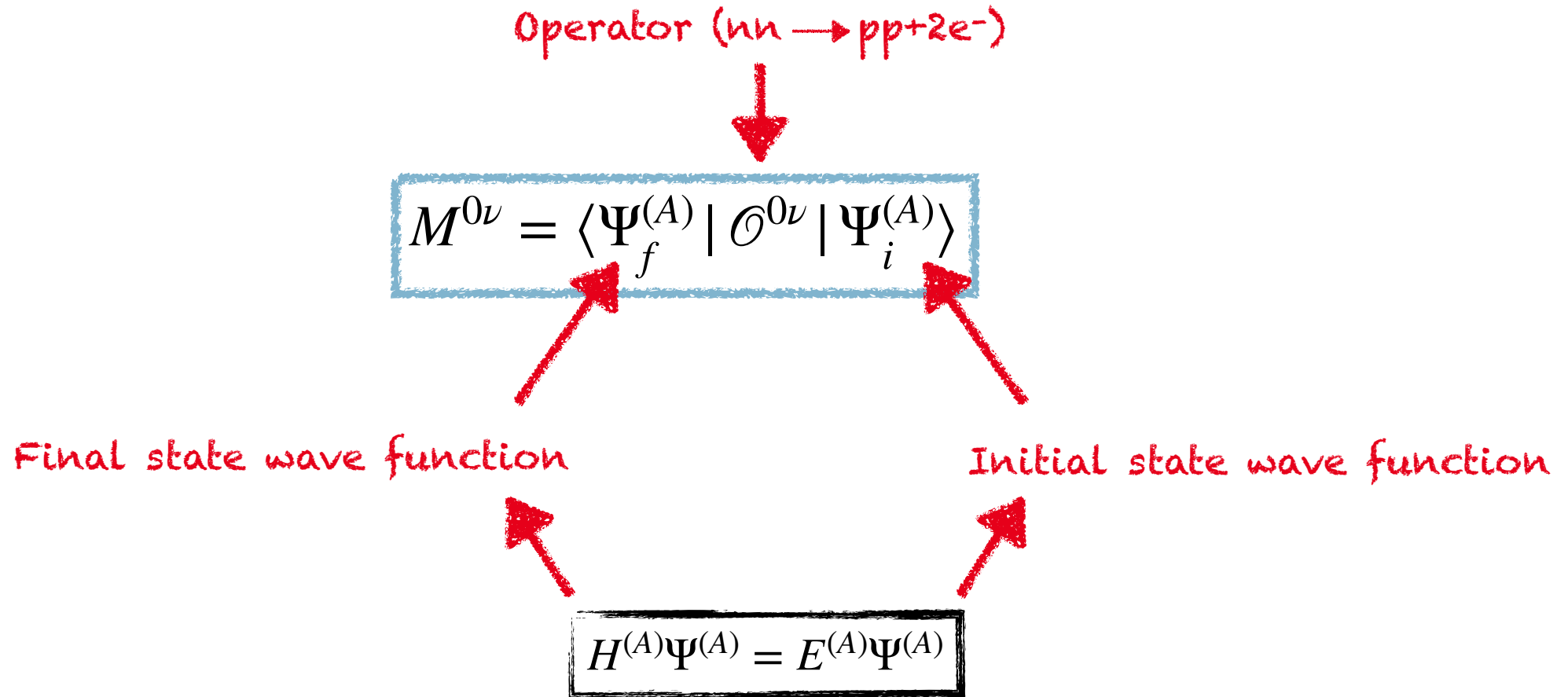


Final state wave function



Initial state wave function

THE NUCLEAR MATRIX ELEMENT





NUCLEAR MATRIX ELEMENT FROM WEAK CURRENTS

Agostini et al., Rev. Mod. Phys. 95, 025002 (2023)

NUCLEAR MATRIX ELEMENT FROM WEAK CURRENTS

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- Starting from the **leading weak currents for one nucleon**

$$\mathcal{J}^0 = \tau[g_V(p^2)]$$

$$\mathbf{J} = \tau \left[g_A(p^2) - g_P(p^2) \frac{\mathbf{p}(\mathbf{p} \cdot \boldsymbol{\sigma})}{p^2 + m_\pi^2} + i g_M(p^2) \frac{\boldsymbol{\sigma} \times \mathbf{p}}{2m_N} \right]$$

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- Using **second-order perturbation theory in the weak interaction**, we get

$$\sqrt{\Gamma_{0\nu\beta\beta}} = \sum_k (U_{ek})^2 m_k \frac{g_A^2}{R} \int d\mathbf{x} \int d\mathbf{y} L^{\mu\rho}(\mathbf{x}, \mathbf{y}) \int d\mathbf{p} e^{i\mathbf{p} \cdot (\mathbf{x} - \mathbf{y})} \frac{R}{g_A^2} \sum_{n,m,a,k} \langle 0_f^+ | \frac{\mathcal{J}_n^{\mu\dagger}(\mathbf{x}) | J_a^\pi \rangle \langle J_a^\pi | \mathcal{J}_m^{\rho\dagger}(\mathbf{y})}{\sqrt{m_k^2 + \mathbf{p}^2} [\sqrt{m_k^2 + \mathbf{p}^2} + E_a^{\text{rel}}]} | 0_i^+ \rangle$$

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Majorana mass, $m_{\beta\beta}$

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Majorana mass, $m_{\beta\beta}$

Phase-space factor, $G^{0\nu}$

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LIGHT-NEUTRINO EXCHANGE

Agostini et al., Rev. Mod. Phys. 95, 025002 (2023)

$$M_L^{0\nu} = \frac{1.2A^{1/3} \text{ fm}}{g_A^2} \langle 0_f^+ | \sum_{m,n} \tau_m^- \tau_n^- [H_F(r) \mathbf{1} + H_{GT}(r) \boldsymbol{\sigma}_n \cdot \boldsymbol{\sigma}_m + H_T(r) S_{nm}] | 0_i^+ \rangle$$

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nn → pp

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nn → *pp* *Fermi, Gamow-Teller and tensor operators*

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nn → *pp* Fermi, Gamow-Teller and tensor operators

■ Neutrino potentials

$$H_X(r) = \frac{2}{\pi} \int dp p^2 j_X(pr) \frac{h_X(p)}{p(p + \langle E \rangle)}, \text{ where } X \in \{F, GT, T\}$$

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$nn \rightarrow pp$
Fermi, Gamow-Teller and tensor operators

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- Where the h functions contain contributions from **vector** (V), **axial-vector** (A), **pseudoscalar** (P) and **magnetic** (M) currents

$$h_F = h_F^{VV}$$

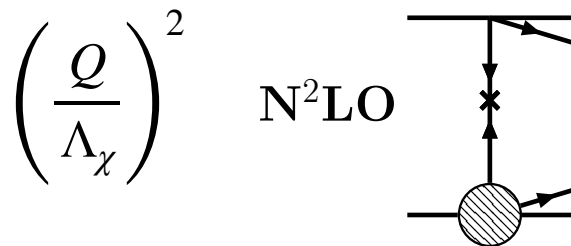
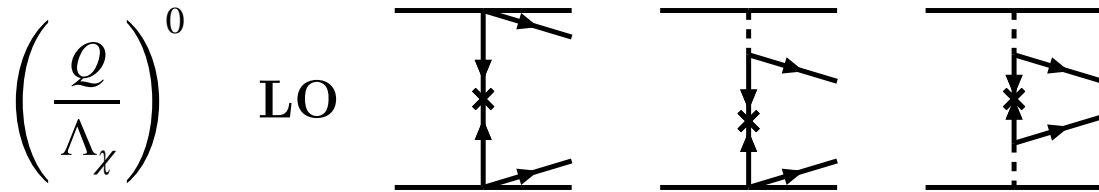
$$h_{GT} = h_{GT}^{AA} + h_{GT}^{AP} + h_{GT}^{PP} + h_{GT}^{MM}$$

$$h_T = h_T^{AP} + h_T^{PP} + h_T^{MM}$$

CHIRAL EFFECTIVE THEORY OPERATORS FOR $0\nu\beta\beta$ DECAY

$$M^{0\nu} = M_L^{0\nu}$$

$$M_L^{0\nu} = M_{\text{GT}}^{0\nu} - \left(\frac{g_V}{g_A}\right)^2 M_F^{0\nu} + M_T^{0\nu}$$



V. Cirigliano et al., *Phys. Rev. Lett.* 120, 202001 (2018), *Phys. Rev. C* 100, 055504 (2019)

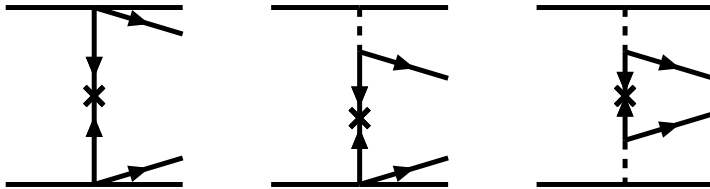
CHIRAL EFFECTIVE THEORY OPERATORS FOR $0\nu\beta\beta$ DECAY

$$M^{0\nu} = M_L^{0\nu} + M_S^{0\nu}$$

$$M_L^{0\nu} = M_{GT}^{0\nu} - \left(\frac{g_V}{g_A} \right)^2 M_F^{0\nu} + M_T^{0\nu}$$

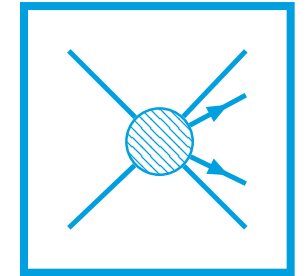
$$\left(\frac{Q}{\Lambda_\chi} \right)^0$$

LO



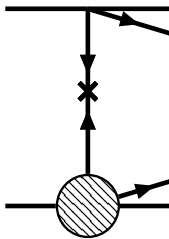
15% – 90 %

Jokiniemi, Soriano, Menéndez,
Phys. Lett. B 823, 136720 (2021)



$$\left(\frac{Q}{\Lambda_\chi} \right)^2$$

N²LO



V. Cirigliano et al., *Phys. Rev. Lett.* 120, 202001 (2018), *Phys. Rev. C* 100, 055504 (2019)

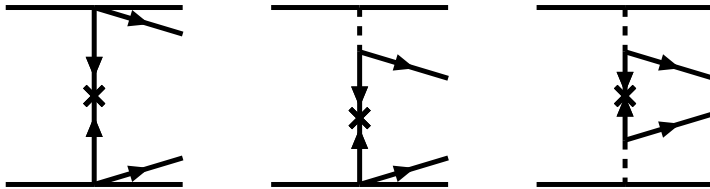
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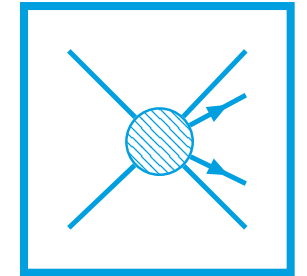
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LO



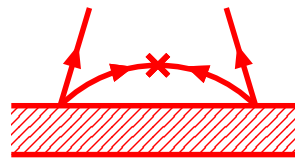
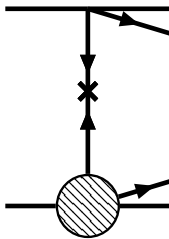
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Jokiniemi, Soriano, Menéndez,
Phys. Lett. B 823, 136720 (2021)



$$\left(\frac{Q}{\Lambda_\chi}\right)^2$$

N²LO



5% – 10 %



V. Cirigliano et al., *Phys. Rev. Lett.* 120, 202001 (2018), *Phys. Rev. C* 100, 055504 (2019)

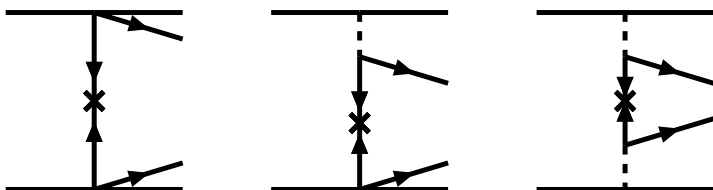
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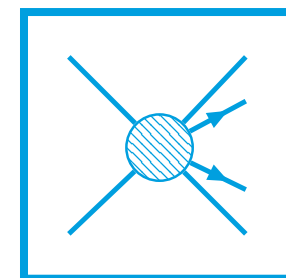
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LO



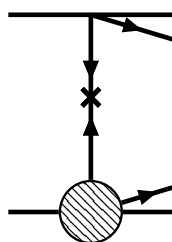
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Jokiniemi, Soriano, Menéndez,
Phys. Lett. B 823, 136720 (2021)

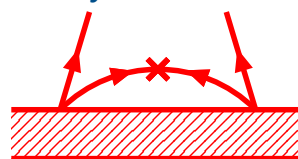


$$\left(\frac{Q}{\Lambda_\chi}\right)^2$$

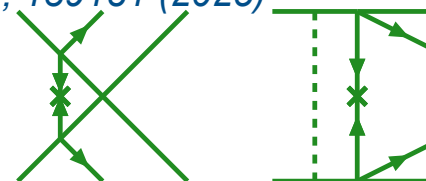
N²LO



Castillo, Jokiniemi, Soriano, Menéndez,
Phys. Lett. B 860, 139181 (2025)

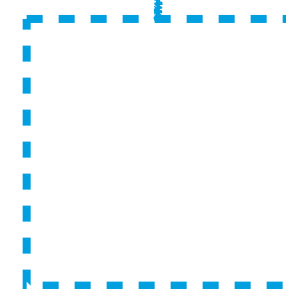


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V. Cirigliano et al., *Phys. Rev. Lett.* 120, 202001 (2018), *Phys. Rev. C* 100, 055504 (2019)

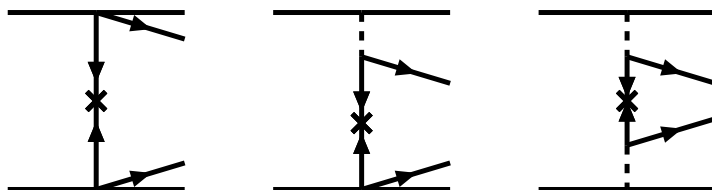
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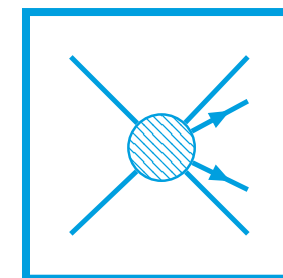
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LO



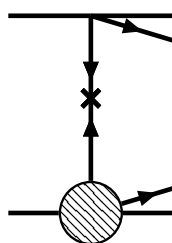
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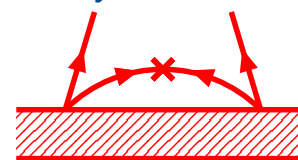


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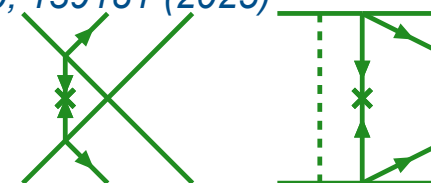
N²LO



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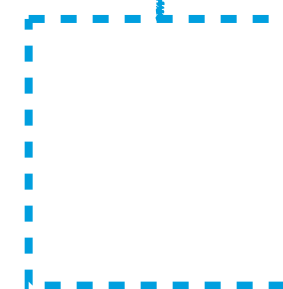


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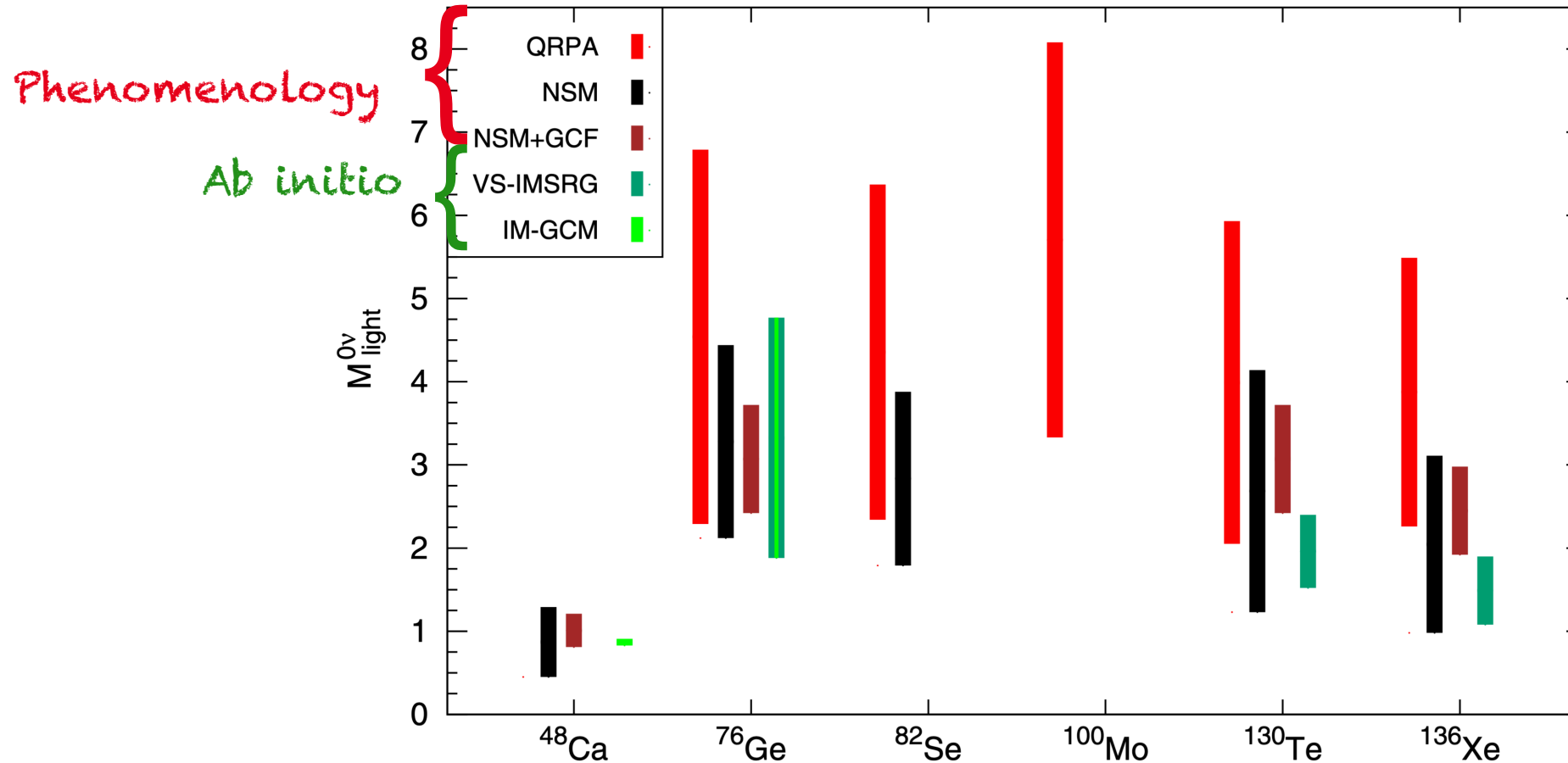


N³LO

3-nucleon potentials *Chambers-Wall et al. arXiv:2510.21564*

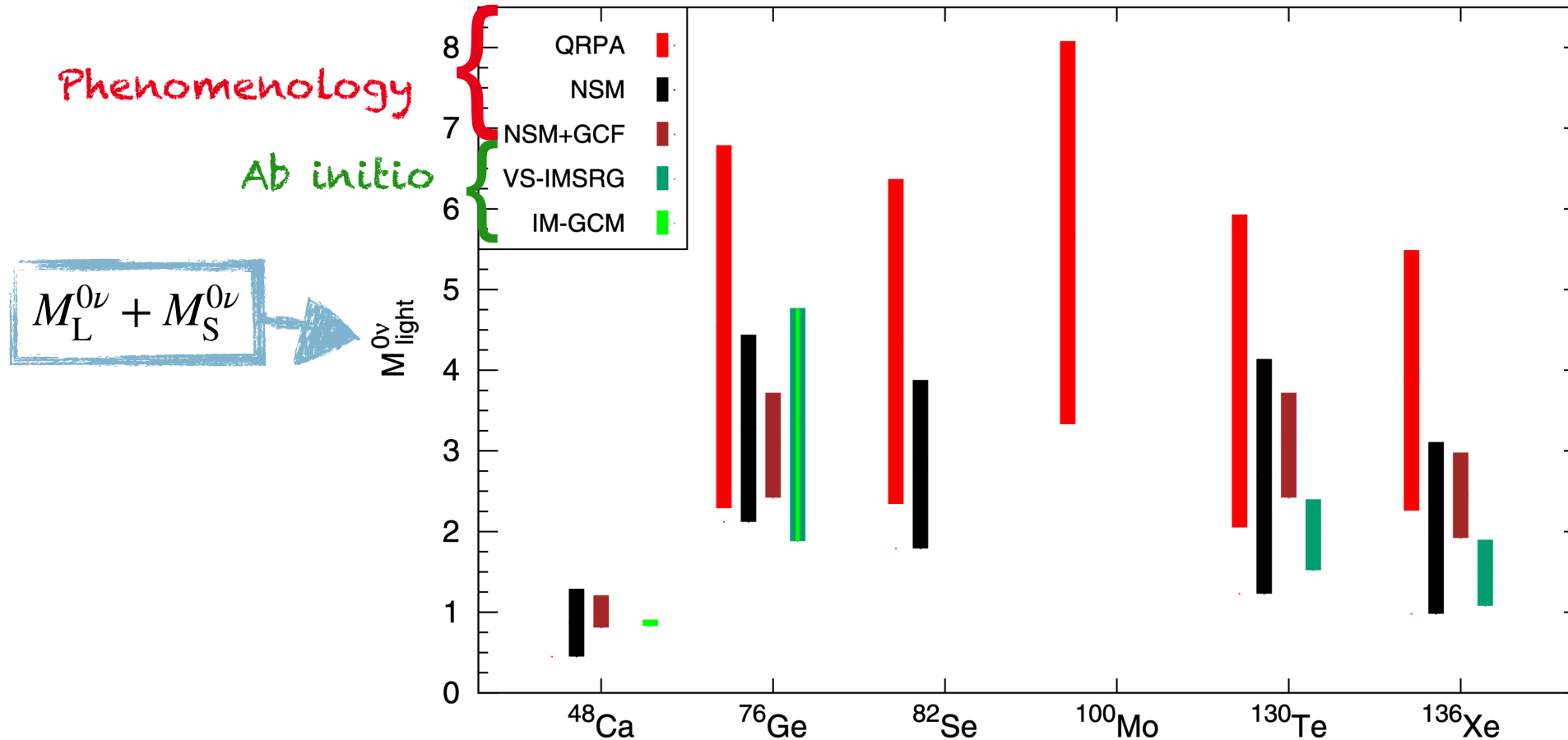
V. Cirigliano et al., Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)

CURRENT STATUS OF THE NUCLEAR MATRIX ELEMENTS



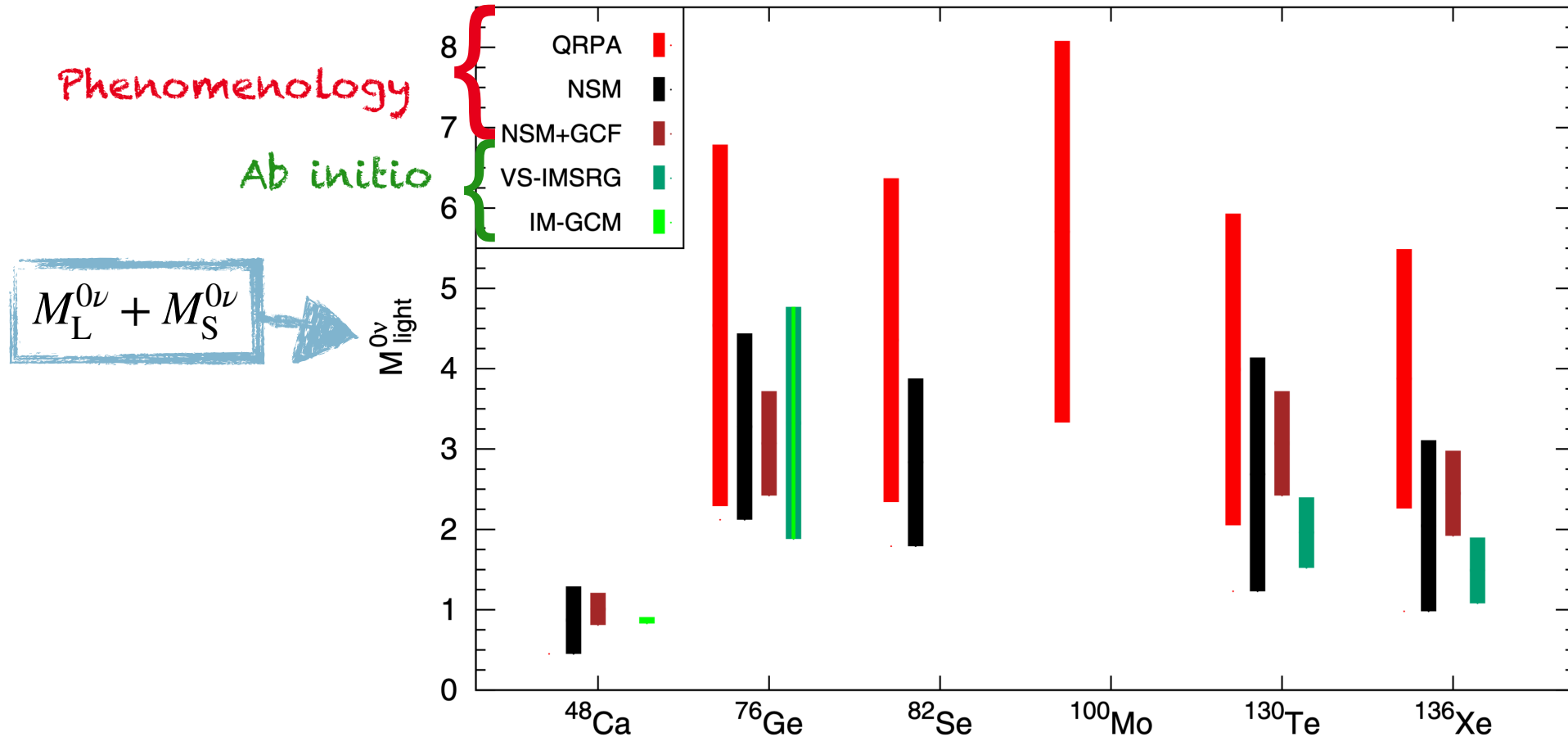
Gómez-Cadenas, Martín-Albo, Menéndez, Mezzetto, Monrabal, Sorel, La Rivista del Nuovo Cimento 46, 619 (2023)

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Gómez-Cadenas, Martín-Albo, Menéndez, Mezzetto, Monrabal, Sorel, *La Rivista del Nuovo Cimento* 46, 619 (2023)

CURRENT STATUS OF THE NUCLEAR MATRIX ELEMENTS

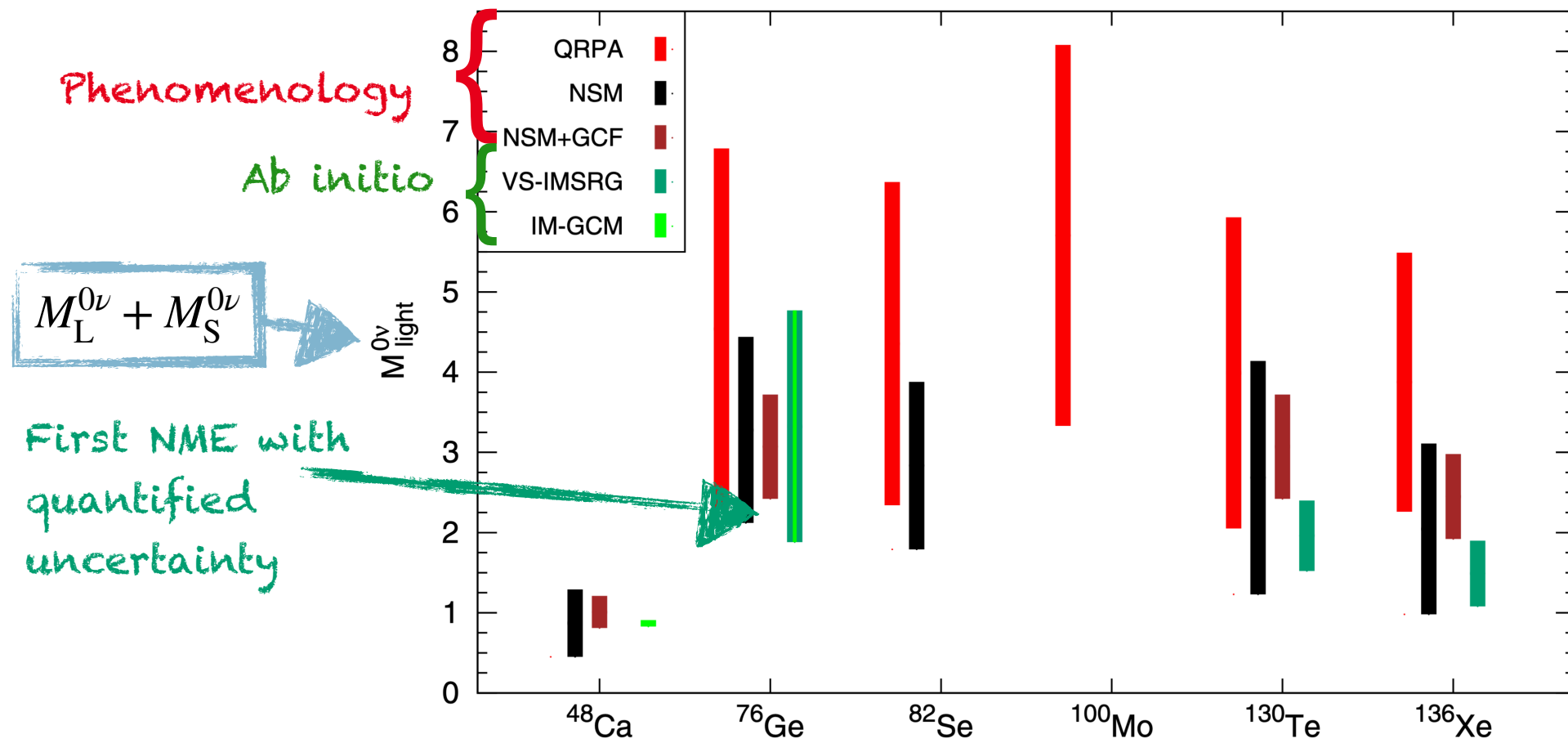


Ranges cover:

- Different **parameters/** nuclear **interactions**
- Different values of g_{ν}^{NN}
- ...

Gómez-Cadenas, Martín-Albo, Menéndez, Mezzetto, Monrabal, Sorel, *La Rivista del Nuovo Cimento* 46, 619 (2023)

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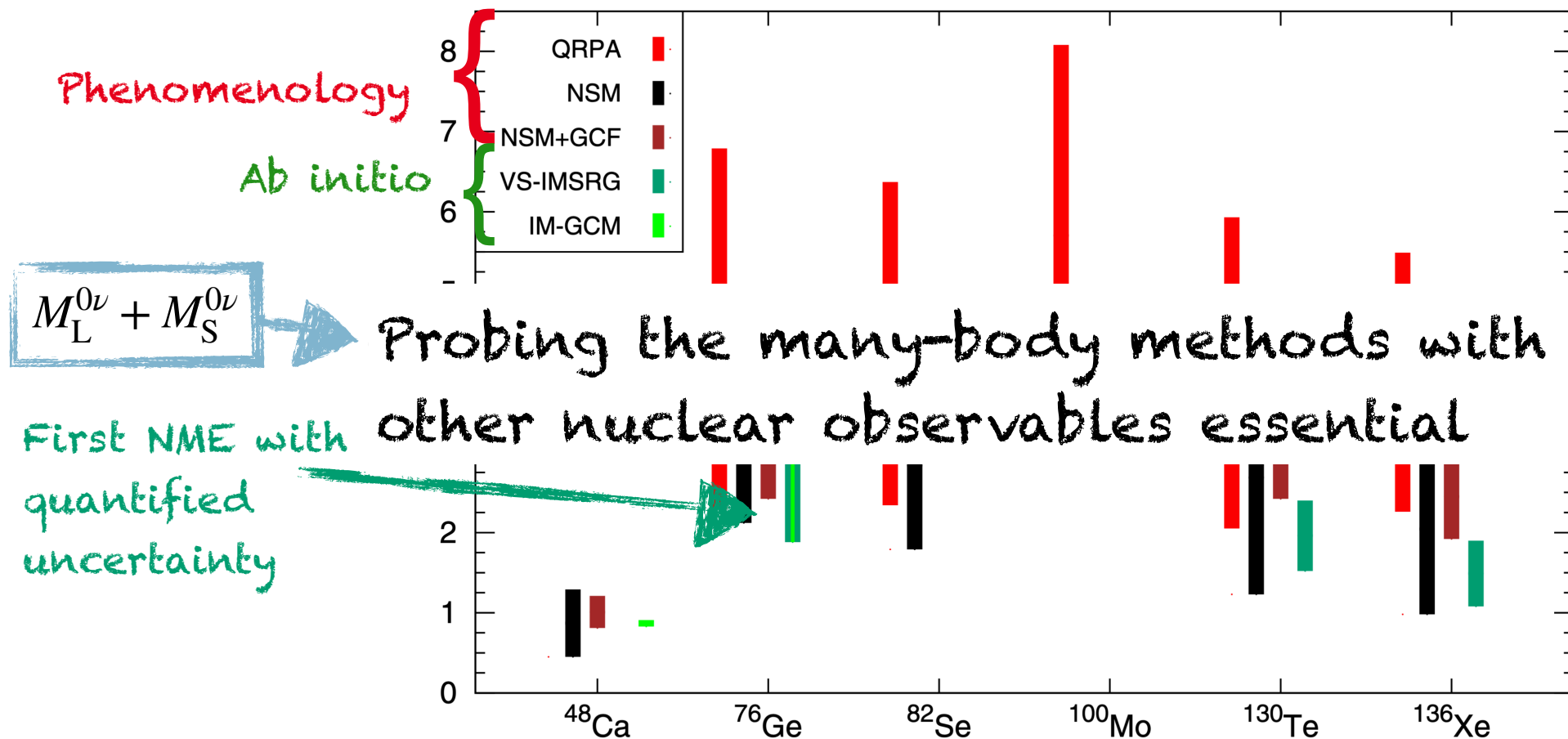


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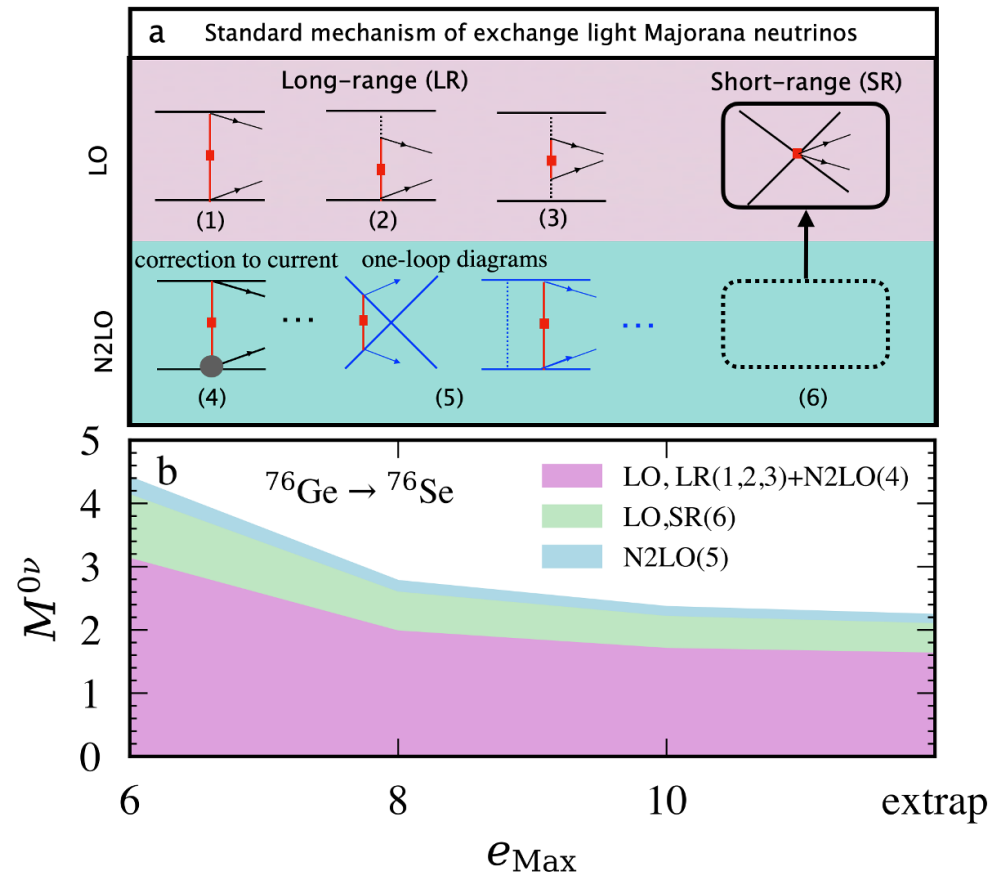
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Gómez-Cadenas, Martín-Albo, Menéndez, Mezzetto, Monrabal, Sorel, *La Rivista del Nuovo Cimento* 46, 619 (2023)

UNCERTAINTY QUANTIFICATION

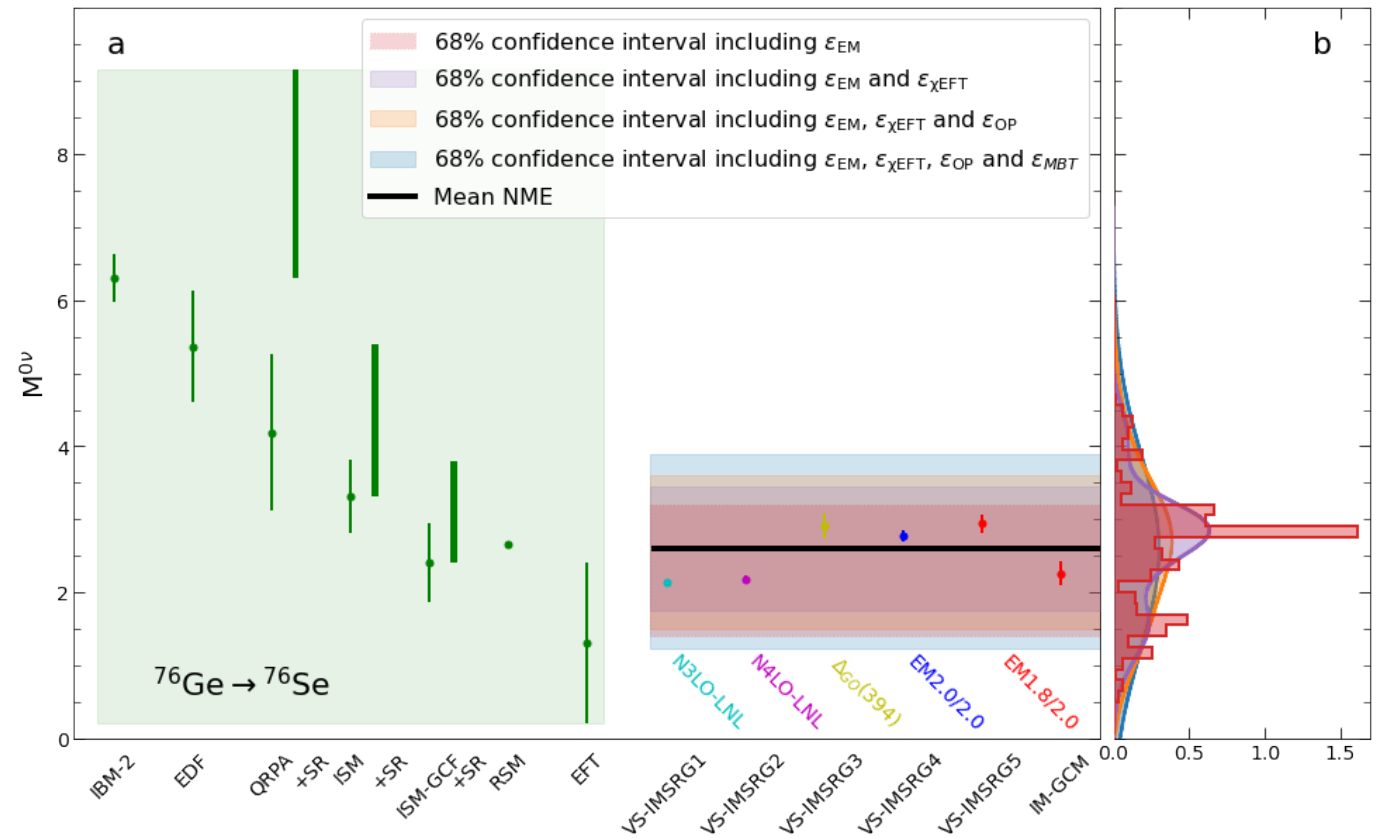
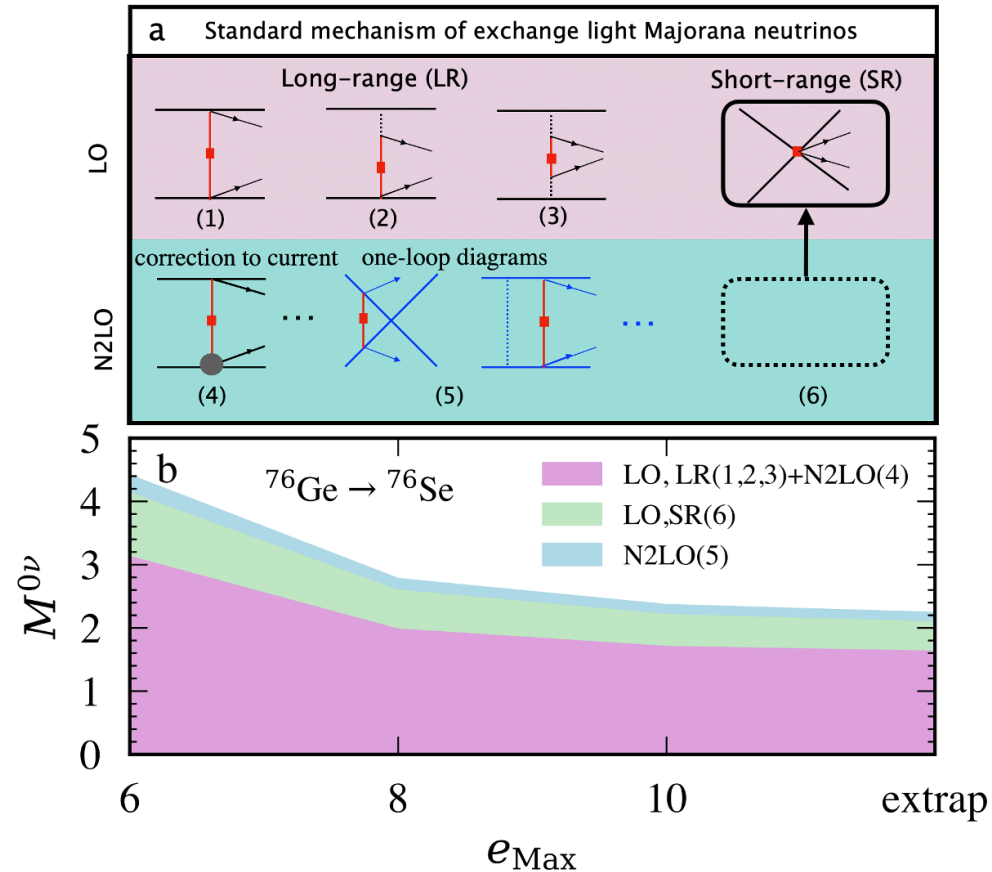
Ab initio calculations based on consistent Hamiltonians and operators based on χ EFT allow for uncertainty quantification



Belley, Yao, Bally, Pitcher, Engel, et al., Phys. Rev. Lett. 132, 182502 (2024)

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Ab initio calculations based on consistent Hamiltonians and operators based on χ EFT allow for uncertainty quantification



Belley, Yao, Bally, Pitcher, Engel, et al., Phys. Rev. Lett. 132, 182502 (2024)

COULD WE LEARN SOMETHING FROM THE STANDARD-MODEL ALLOWED DOUBLE-BETA DECAY?



CORRELATIONS BETWEEN $0\nu\beta\beta$ AND $2\nu\beta\beta$ DECAYS



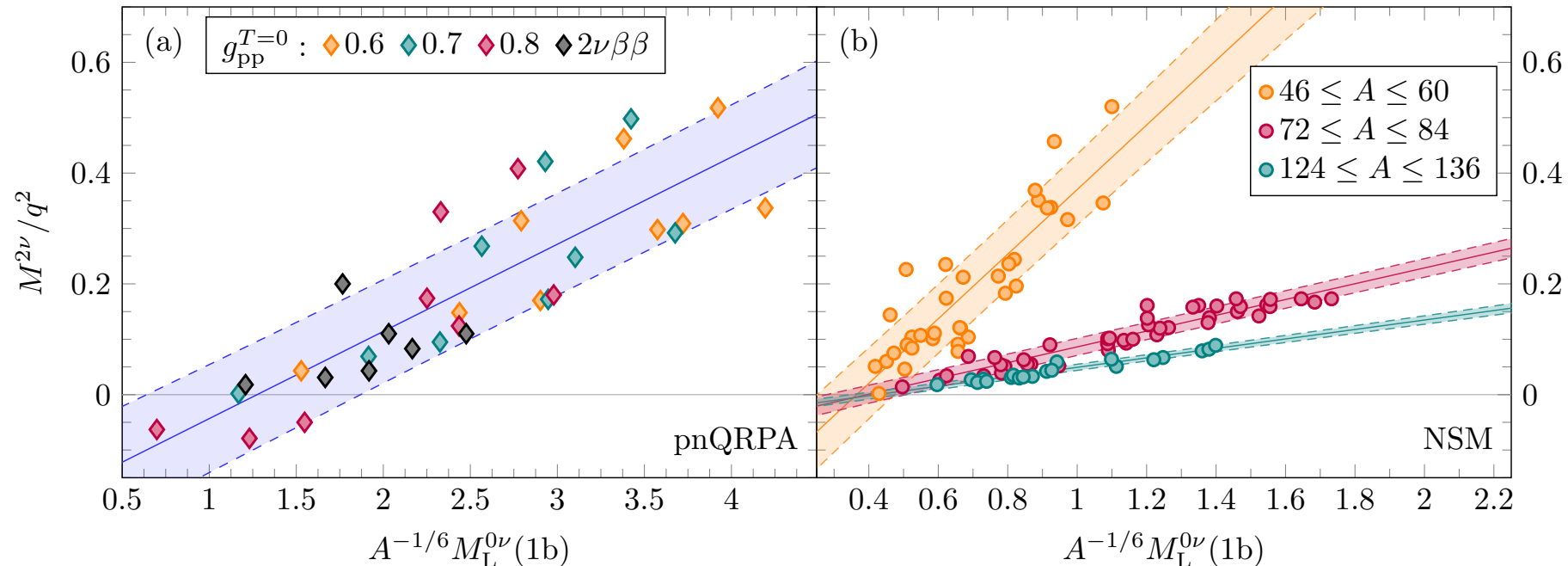
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$$M^{2\nu} = \sum_n \frac{\langle 0_f^+ \| \sum_j \tau_j^- \sigma_j \| 1_n^+ \rangle \langle 1_n^+ \| \sum_k \tau_k^- \sigma_k \| 0_i^+ \rangle}{E_n - (E_i + E_f)/2}$$

CORRELATIONS BETWEEN $0\nu\beta\beta$ AND $2\nu\beta\beta$ DECAYS

- $2\nu\beta\beta$ decay found to be correlated with $0\nu\beta\beta$ decay

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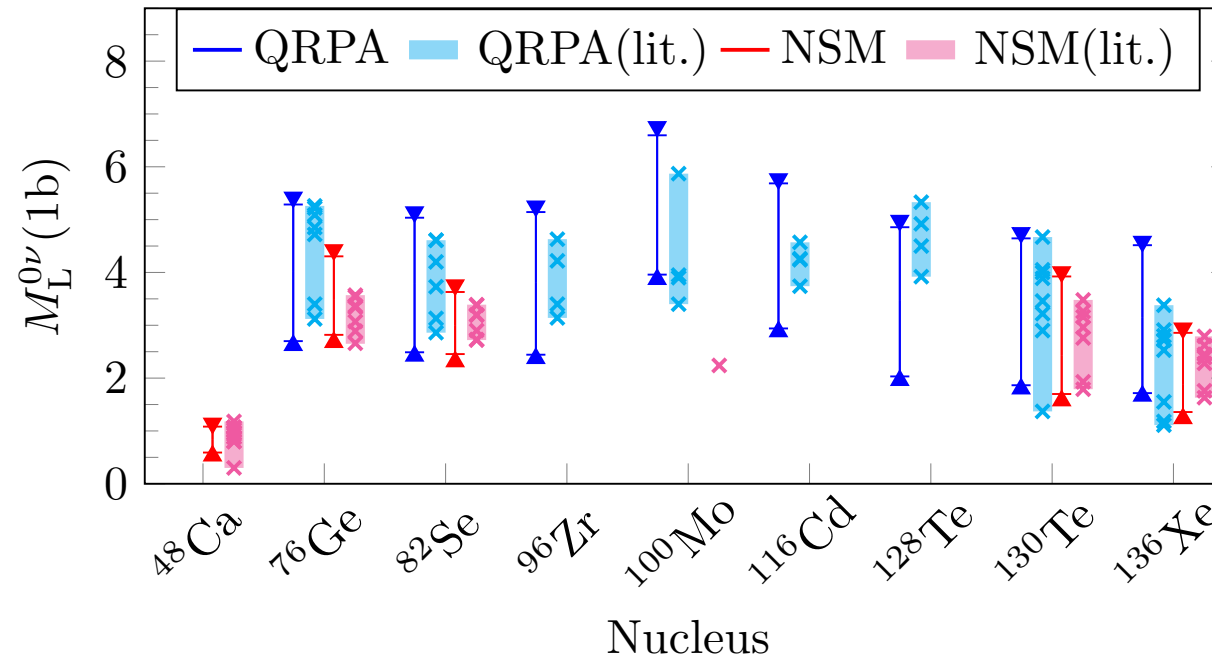


Jokiniemi, Romeo, Soriano, Menéndez, *Phys. Rev. C* 107, 044305 (2023)

CORRELATIONS BETWEEN $0\nu\beta\beta$ AND $2\nu\beta\beta$ DECAYS

- $2\nu\beta\beta$ decay found to be correlated with $0\nu\beta\beta$ decay
- We can use existing data to estimate $0\nu\beta\beta$ -decay NMEs with uncertainties

$$M^{2\nu} = \sum_n \frac{\langle 0_f^+ \| \sum_j \tau_j^- \sigma_j \| 1_n^+ \rangle \langle 1_n^+ \| \sum_k \tau_k^- \sigma_k \| 0_i^+ \rangle}{E_n - (E_i + E_f)/2}$$



Jokiniemi, Romeo, Soriano, Menéndez, *Phys Rev. C* 107, 044305 (2023)

CORRELATIONS BETWEEN $0\nu\beta\beta$ AND $2\nu\beta\beta$ DECAYS

- Correlations also found in statistical shell-model studies in

- ^{48}Ca

Horoi, Neacsu, Stoica, Phys. Rev. C 106, 054302 (2022)

- ^{76}Ge

Horoi, Neacsu, arXiv:2605.21657

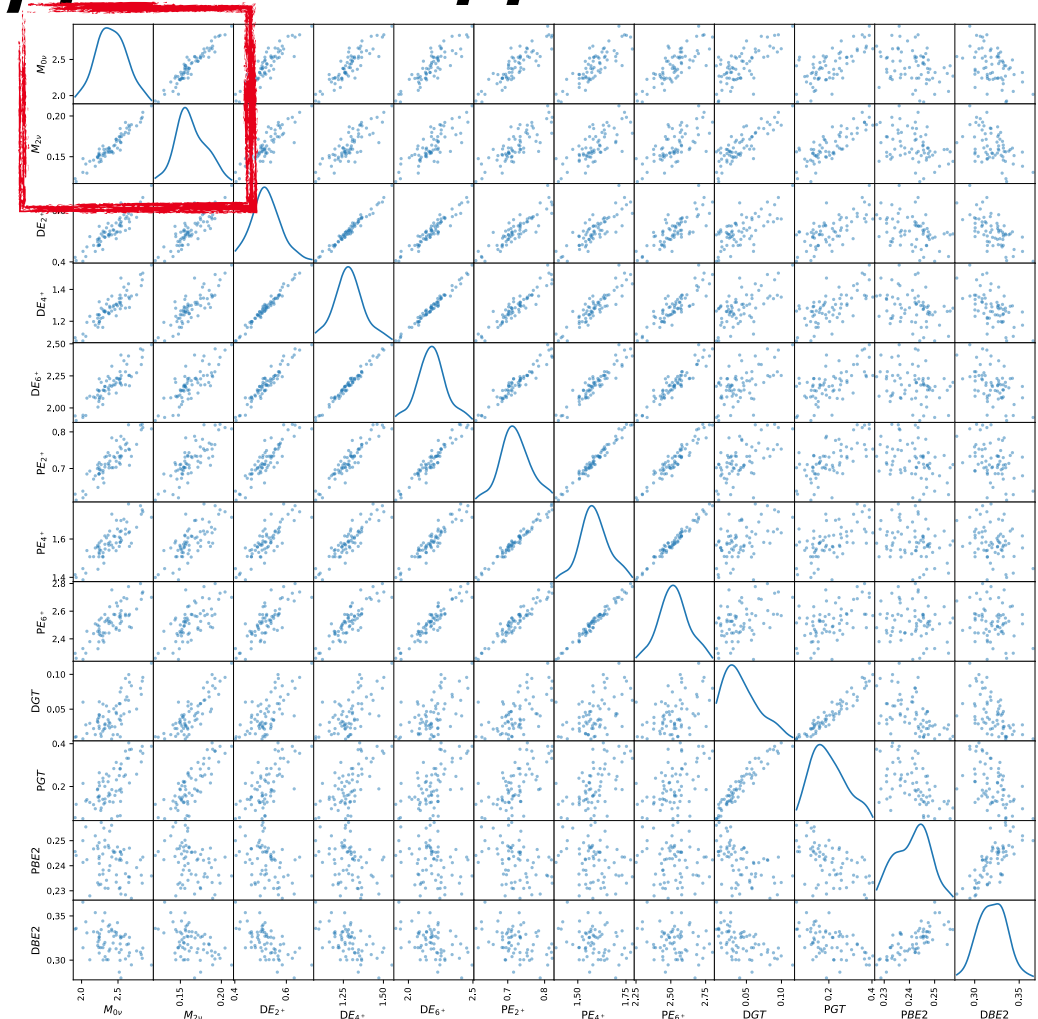
- ^{82}Se

Neacsu, Horoi, Symmetry 2024, 16(8), 974

- ^{136}Xe

Horoi, Neacsu, Stoica, Phys. Rev. C 107, 045501 (2023)

Horoi, Universe 10 (6), 252



Horoi, Neacsu, arXiv:2605.21657

AB INITIO CORRELATION BETWEEN $0\nu\beta\beta$ AND $2\nu\beta\beta$ DECAYS

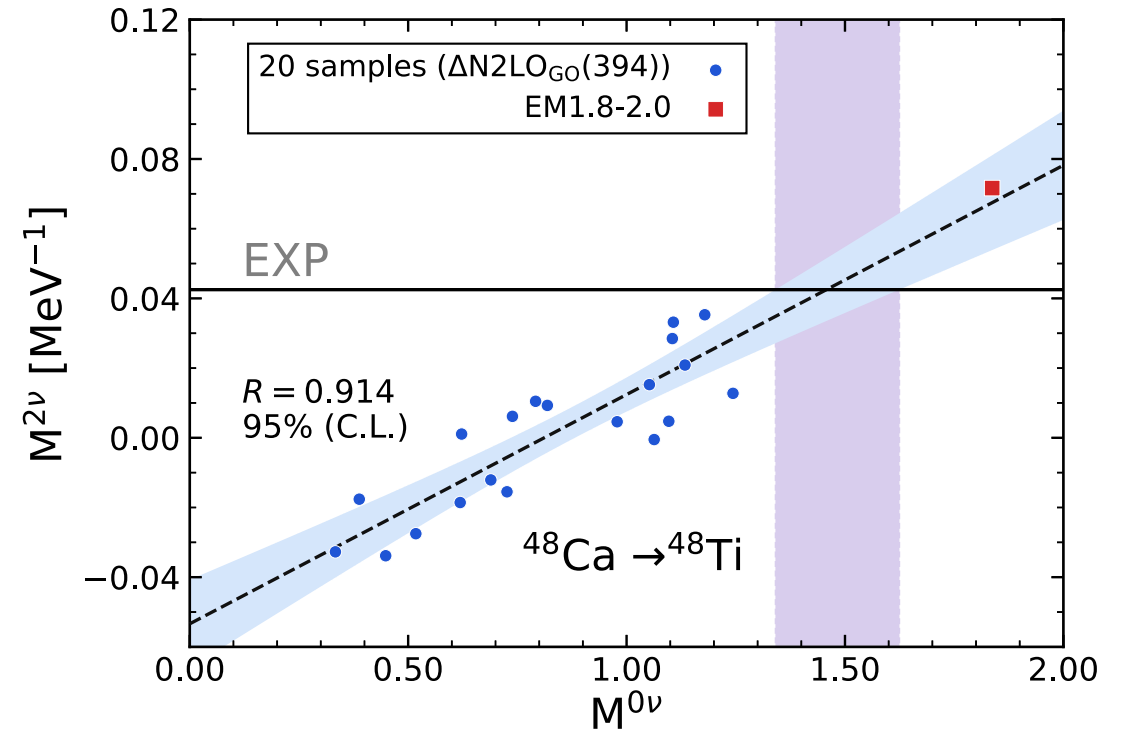
- In-Medium No-Core Configuration Interaction (IM-NCCI) method:

solve $H^{(A)} |\Psi\rangle = E |\Psi\rangle$ with

$$|\Psi\rangle = D_0 |\Phi\rangle + \sum_{m,i} a_m^\dagger a_i |\Phi\rangle + \sum_{mnij} a_m^\dagger a_n^\dagger a_i a_j |\Phi\rangle + \dots$$

and χ EFT Hamiltonians

$$H^{(A)} = \sum_{i=1}^A \frac{p_i^2}{2m} + \sum_{i<j=1}^A V_{ij}^{\text{NN}}(\mathbf{r}_i - \mathbf{r}_j) + \sum_{i<j<k=1}^A V_{ijk}^{\text{3N}}$$



Lian, Ding, Bai, Yao, arXiv:2605.19479

AB INITIO CORRELATION BETWEEN $0\nu\beta\beta$ AND $2\nu\beta\beta$ DECAYS

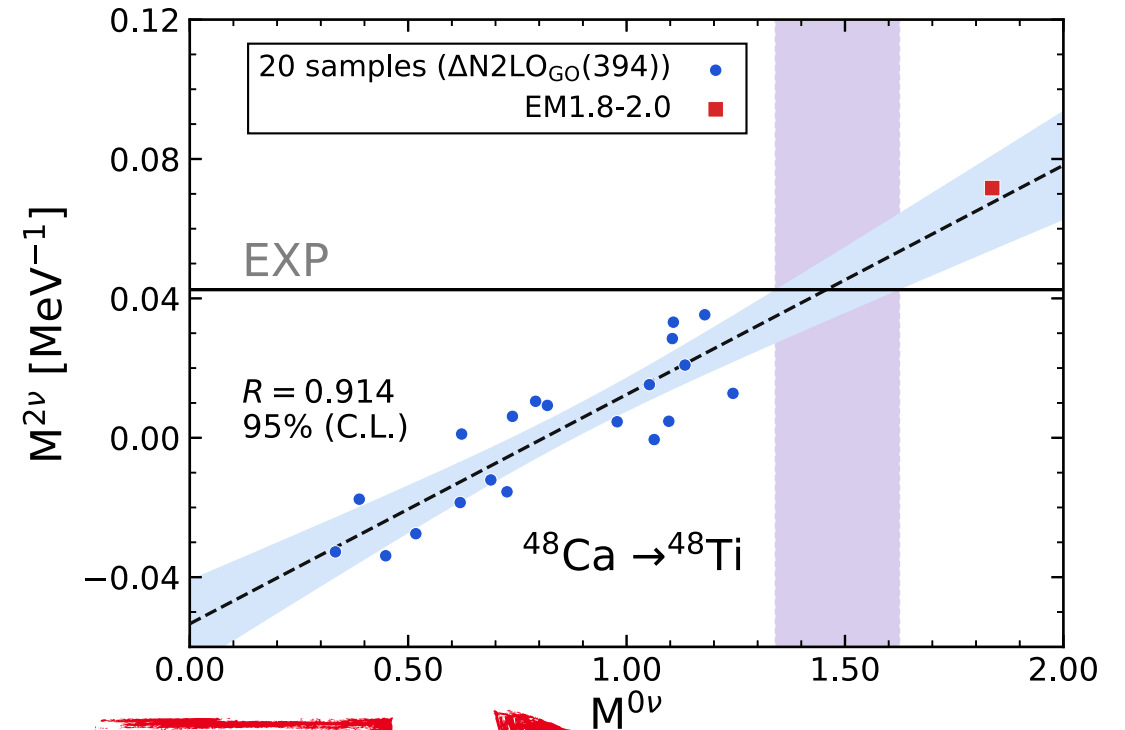
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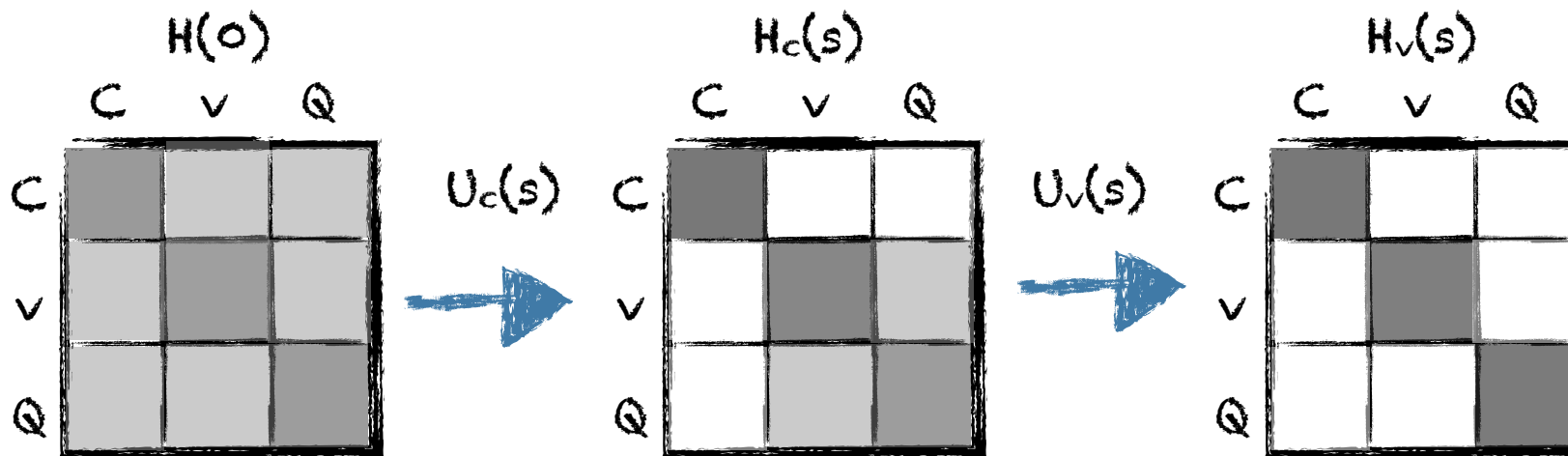
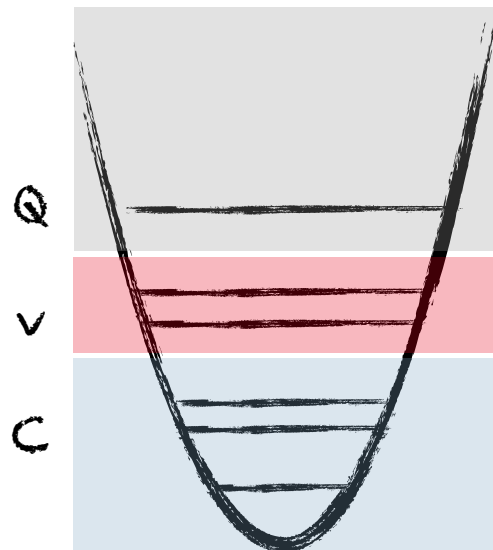
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$$M_L^{0\nu} + M_S^{0\nu}$$

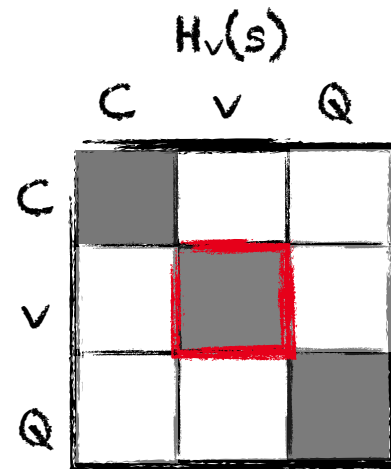
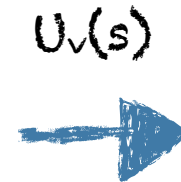
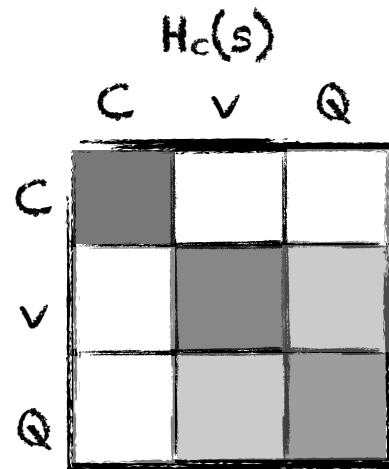
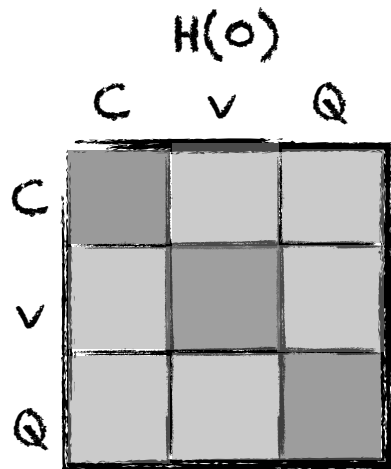
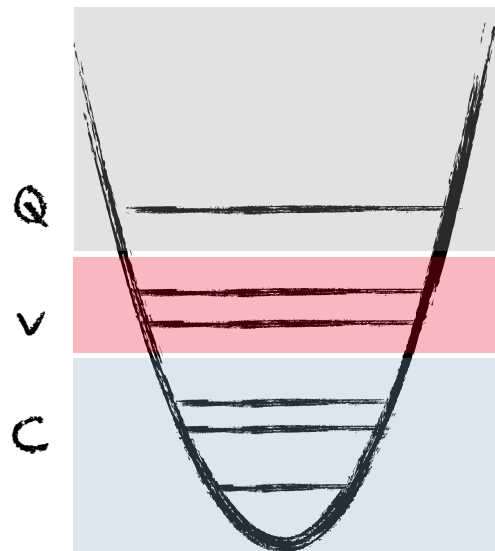
Lian, Ding, Bai, Yao, arXiv:2605.19479

$2\nu\beta\beta$ DECAY WITH VS-IMSRG(2)



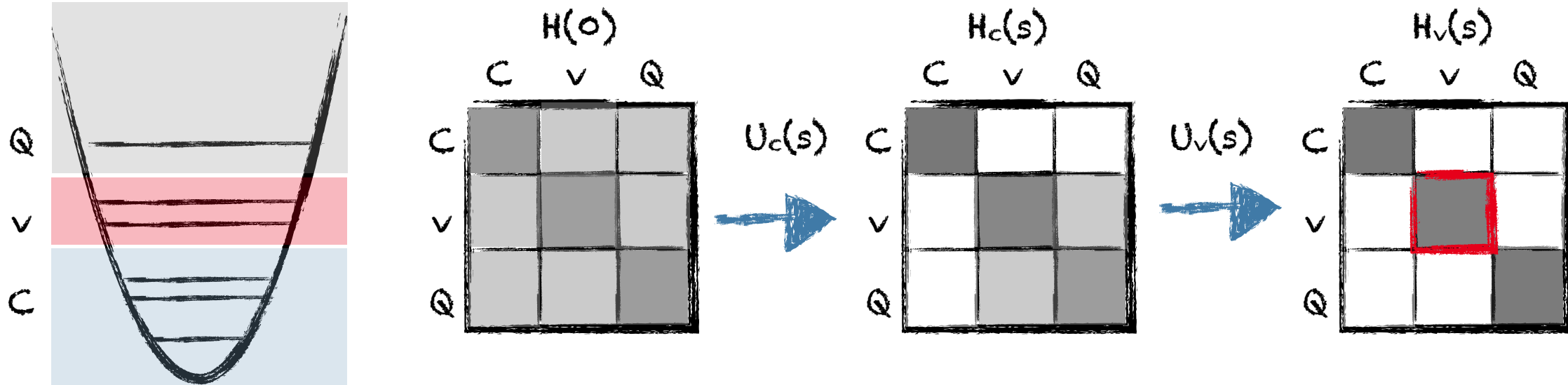
Stroberg et al., Phys. Rev. Lett. 118, 032502 (2017)

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Stroberg et al., Phys. Rev. Lett. 118, 032502 (2017)

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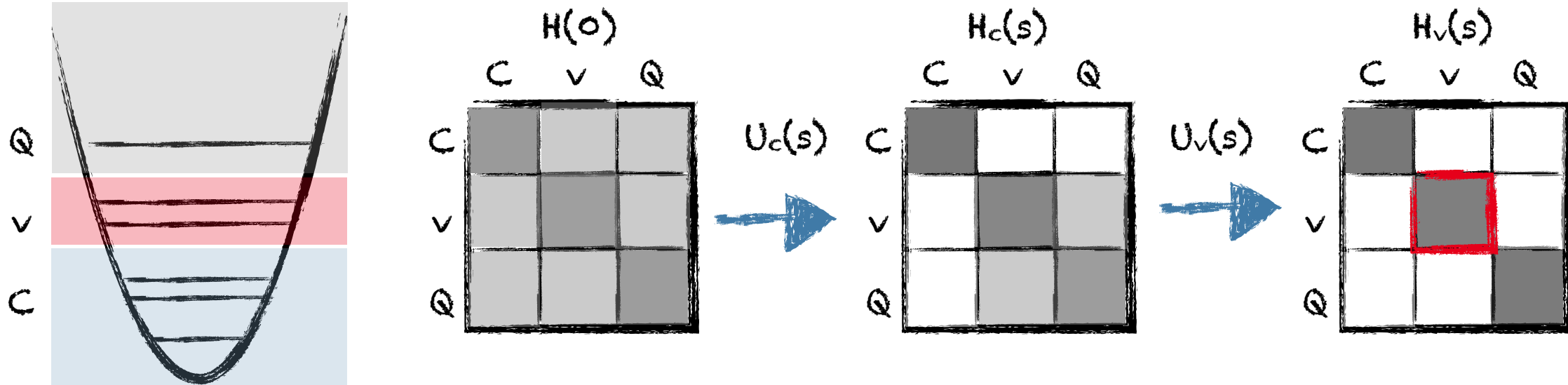


- Start from normal-ordered Hamiltonian

$$H(0) = E_0 + \sum_{ij} f_{ij} \{a_i^\dagger a_j\} + \frac{1}{4} \sum_{ijkl} \Gamma_{ijkl} \{a_i^\dagger a_j^\dagger a_l a_k\} \left(+ \frac{1}{36} \sum_{ijklmn} W_{ijklmn} \{a_i^\dagger a_j^\dagger a_k^\dagger a_n a_m a_l\} \right)$$

Stroberg et al., Phys. Rev. Lett. 118, 032502 (2017)

$2\nu\beta\beta$ DECAY WITH VS-IMSRG(2)



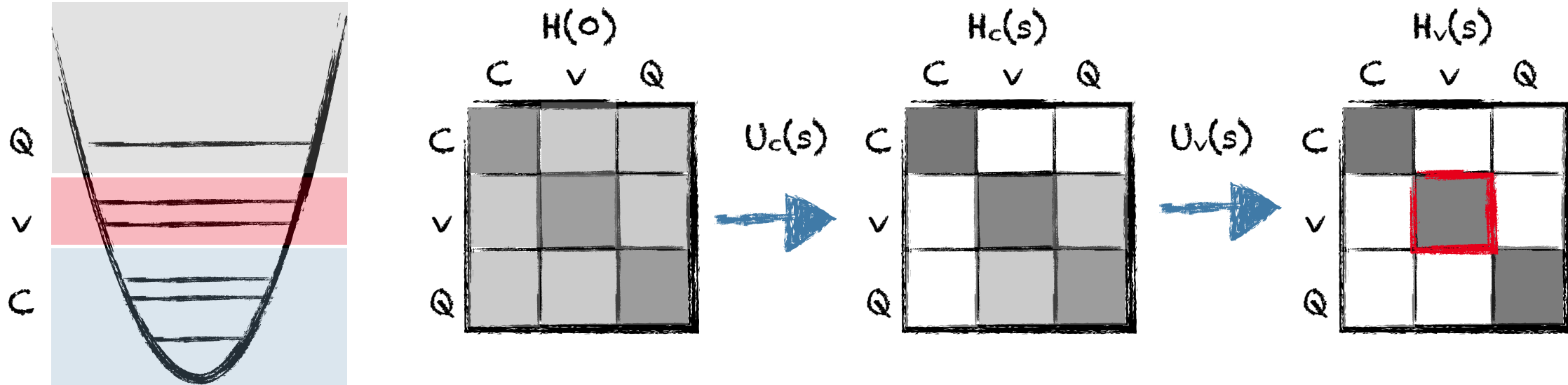
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- Hamiltonian truncated at two-body level: $H(s) = e^\Omega H e^{-\Omega} = H + [\Omega, H]_{0,1,2} + \frac{1}{2} [\Omega, [\Omega, H]]_{0,1,2} + \dots$

Stroberg et al., Phys. Rev. Lett. 118, 032502 (2017)

$2\nu\beta\beta$ DECAY WITH VS-IMSRG(2)



- Start from normal-ordered Hamiltonian

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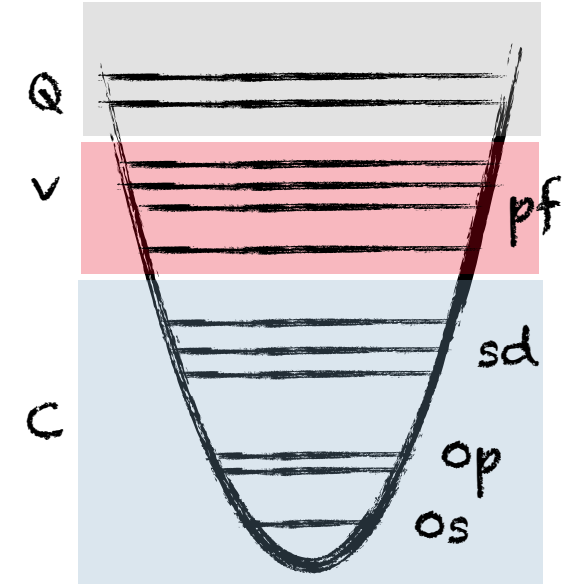
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- Operators transformed consistently $\mathcal{O}(s) = e^\Omega \mathcal{O} e^{-\Omega}$

Stroberg et al., Phys. Rev. Lett. 118, 032502 (2017)

MULTI-SHELL VALENCE SPACE

Miyagi, Stroberg, Holt, Shimizu, Phys. Rev. C 102, 034320 (2020)

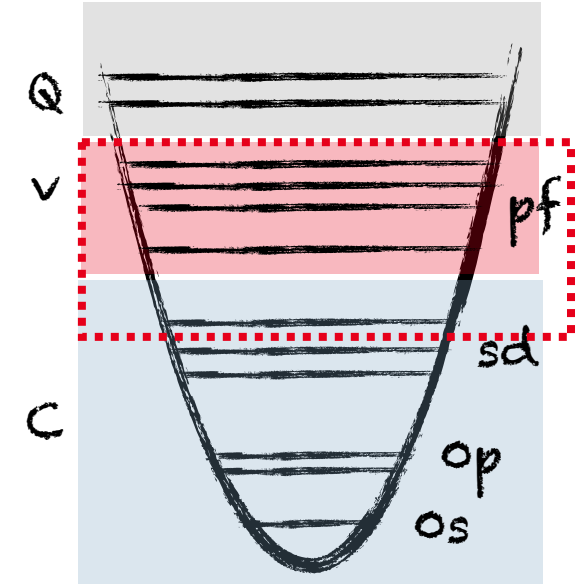
$$\frac{dH(s)}{ds} = [\eta(s), H(s)]$$



MULTI-SHELL VALENCE SPACE

Miyagi, Stroberg, Holt, Shimizu, Phys. Rev. C 102, 034320 (2020)

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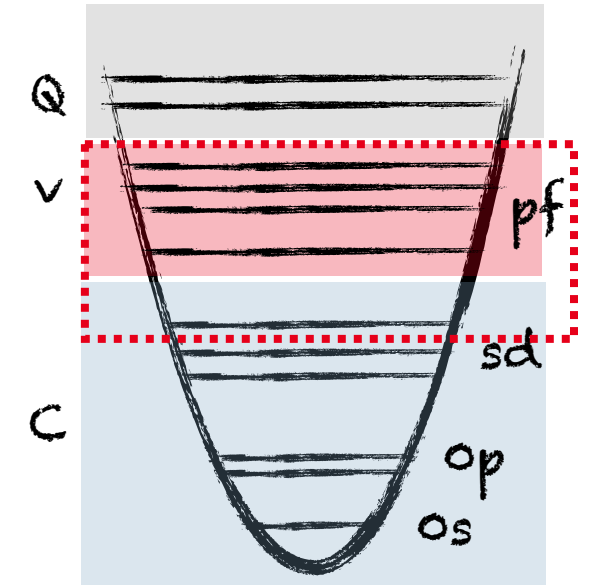
MULTI-SHELL VALENCE SPACE

Miyagi, Stroberg, Holt, Shimizu, Phys. Rev. C 102, 034320 (2020)

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

- For the multi-shell valence space, we use the generator

$$\eta = \sum_{ai} \{a_a^\dagger a_i\} + \sum_{abij} \{a_a^\dagger a_b^\dagger a_j a_i\} - \text{h.c.},$$



MULTI-SHELL VALENCE SPACE

Miyagi, Stroberg, Holt, Shimizu, Phys. Rev. C 102, 034320 (2020)

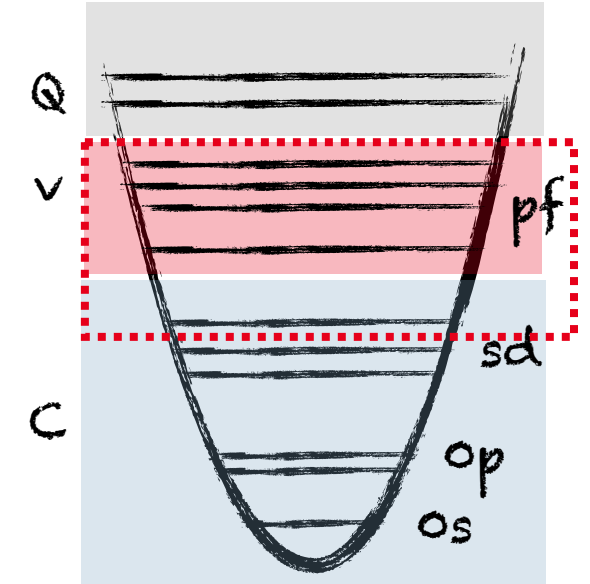
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$$\eta = \sum_{ai} \{a_a^\dagger a_i\} + \sum_{abij} \{a_a^\dagger a_b^\dagger a_j a_i\} - \text{h.c.},$$

- where

$$\eta_{ai} = \frac{1}{2} \arctan \left(\frac{2f_{ai}}{f_{aa} - f_{ii} + \Gamma_{aiai} + \Delta} \right), \quad \eta_{abij} = \frac{1}{2} \arctan \left(\frac{2\Gamma_{abij}}{f_{aa} + f_{bb} - f_{ii} - f_{jj} + G_{abij} + \Delta} \right)$$



MULTI-SHELL VALENCE SPACE

Miyagi, Stroberg, Holt, Shimizu, Phys. Rev. C 102, 034320 (2020)

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

- For the multi-shell valence space, we use the generator

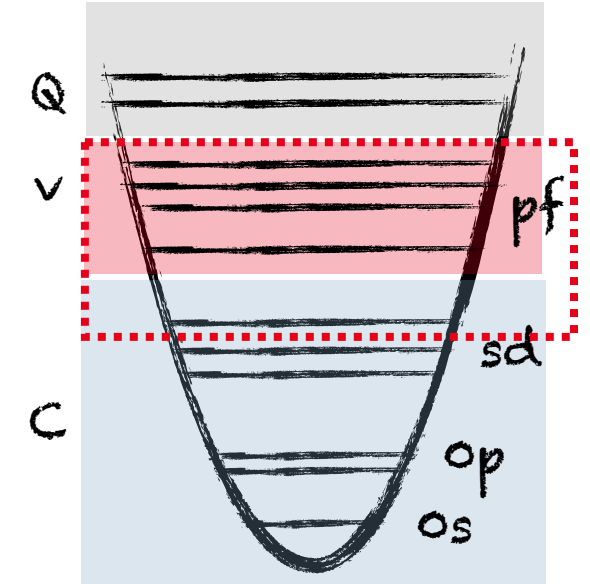
$$\eta = \sum_{ai} \{a_a^\dagger a_i\} + \sum_{abij} \{a_a^\dagger a_b^\dagger a_j a_i\} - \text{h.c.},$$

- where

$$\eta_{ai} = \frac{1}{2} \arctan\left(\frac{2f_{ai}}{f_{aa} - f_{ii} + \Gamma_{aiai} + \Delta}\right), \quad \eta_{abij} = \frac{1}{2} \arctan\left(\frac{2\Gamma_{abij}}{f_{aa} + f_{bb} - f_{ii} - f_{jj} + G_{abij} + \Delta}\right)$$

- To remove spurious centre-of-mass motion, we modify the Hamiltonian as

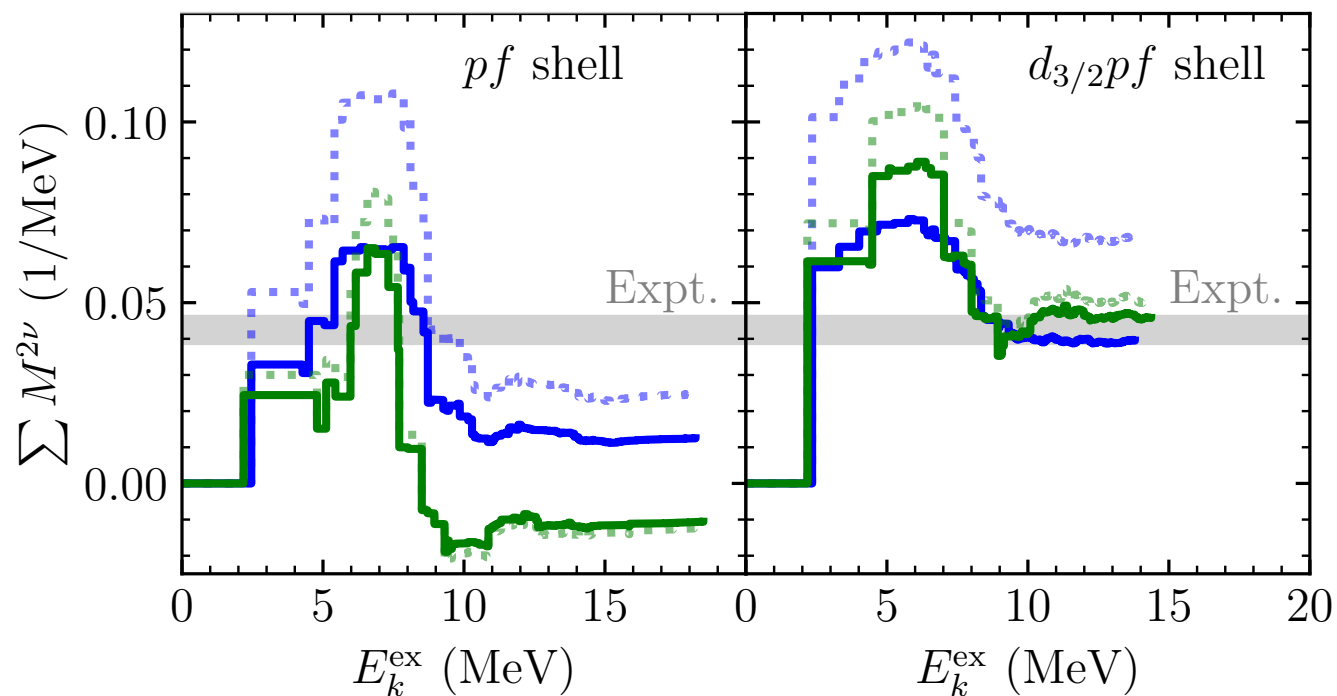
$$H = H_{\text{intr.}} + \beta H_{\text{c.m.}}$$



$2\nu\beta\beta$ DECAY WITH VS-IMSRG(2)

$$M^{2\nu} = \sum_n \frac{\langle 0_f^+ \| \mathbf{GT}^- \| 1_n^+ \rangle \langle 1_n^+ \| \mathbf{GT}^- \| 0_i^+ \rangle}{E_n - (E_i + E_f)/2}$$

- 1.8/2.0 (EM), 1BC
- $\Delta N^2\text{LO}_{\text{GO}}$ (394), 1BC
- 1.8/2.0 (EM), 1BC+2BC
- $\Delta N^2\text{LO}_{\text{GO}}$ (394), 1BC+2BC



Li, Jokiniemi, Schwenk, arXiv:2607.11733

$2\nu\beta\beta$ DECAY WITH VS-IMSRG(2)

- Two different χ EFT NN+3N interactions:

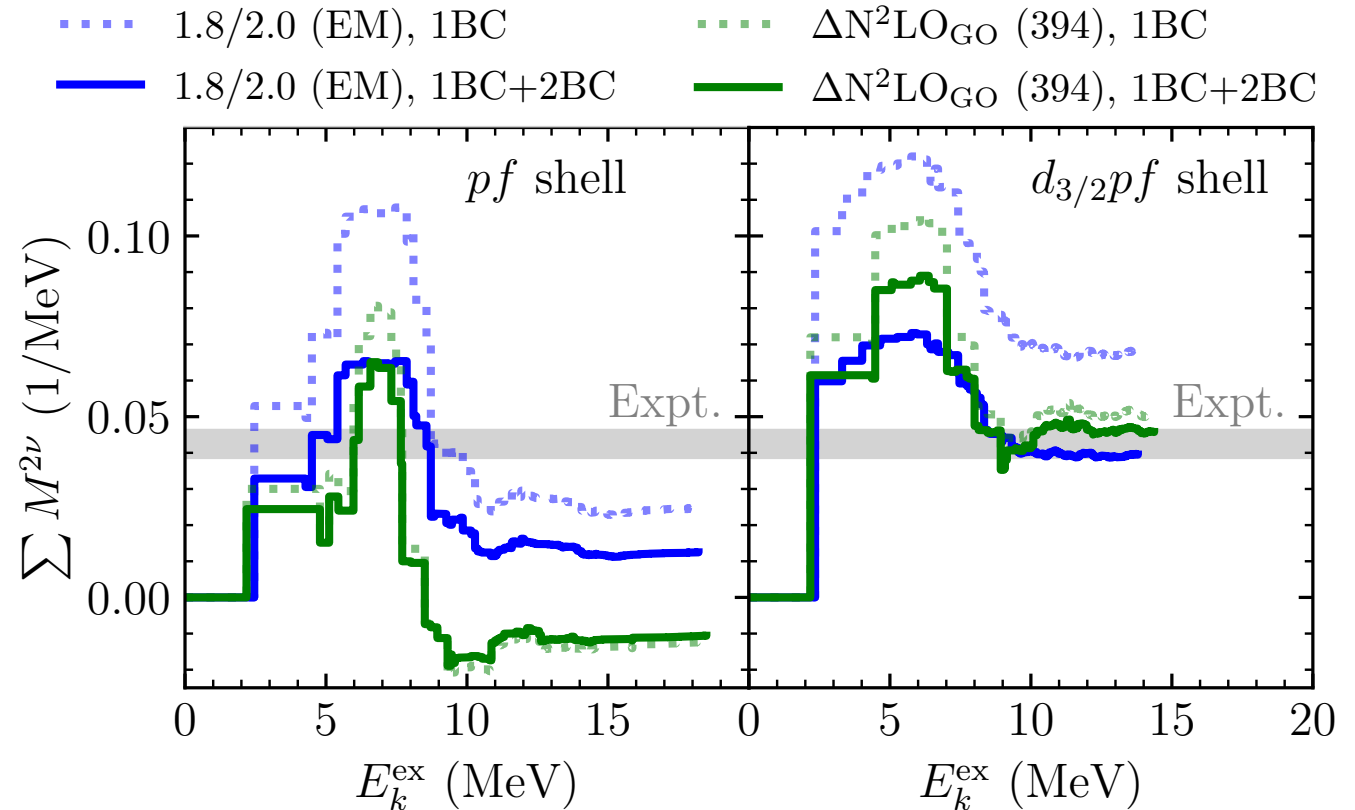
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- One- and two-body axial currents

$$\mathbf{J} = \mathbf{J}_{1b} + \mathbf{J}_{2b}^{ct} + \mathbf{J}_{1b}^{1\pi}$$

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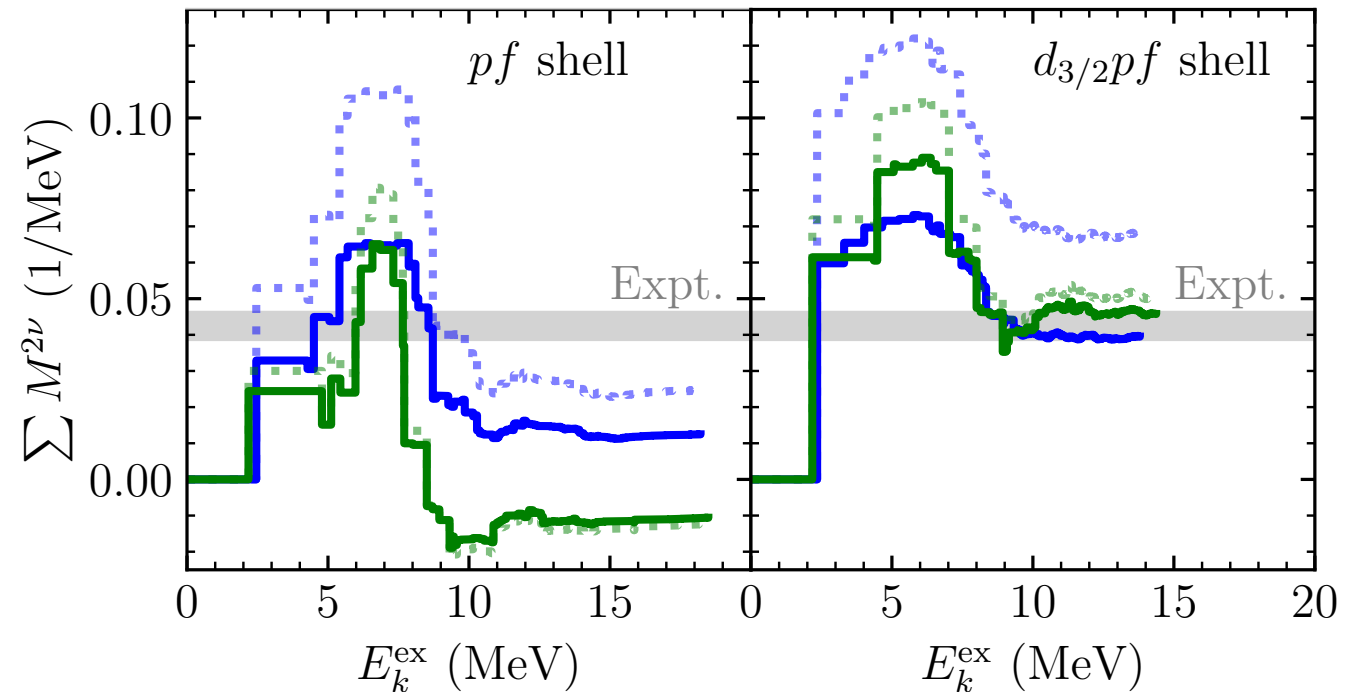
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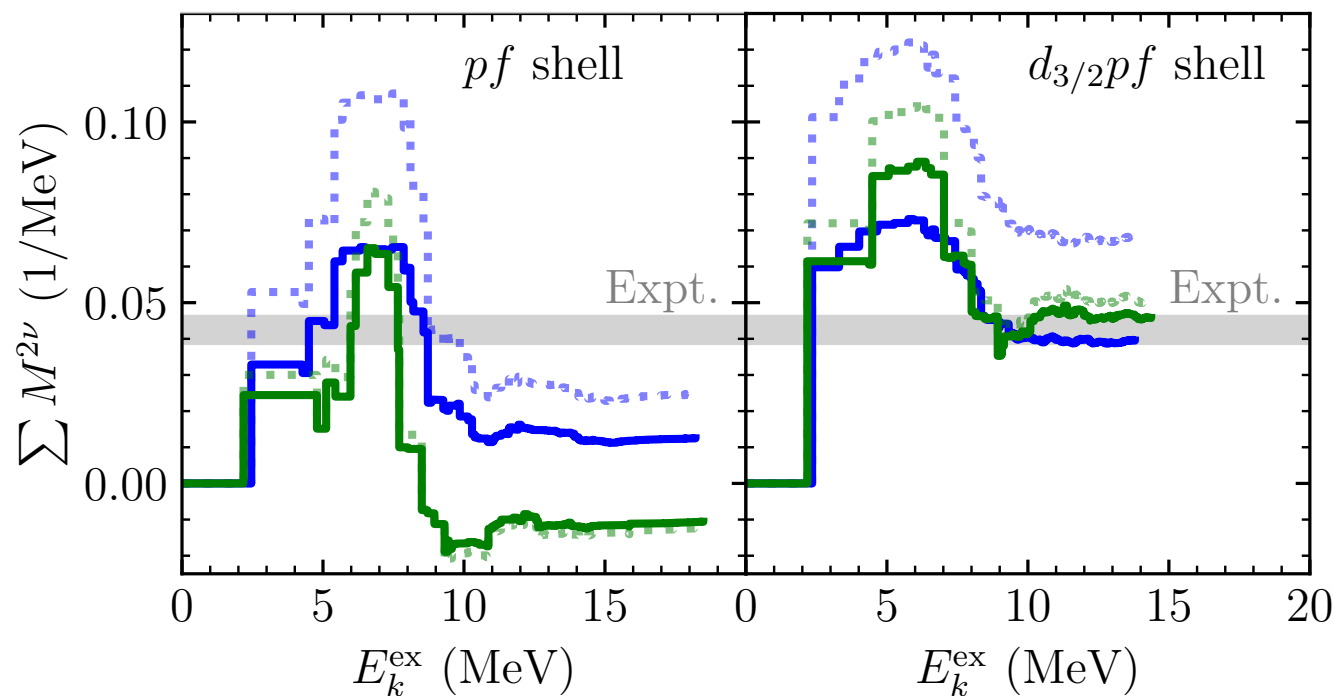
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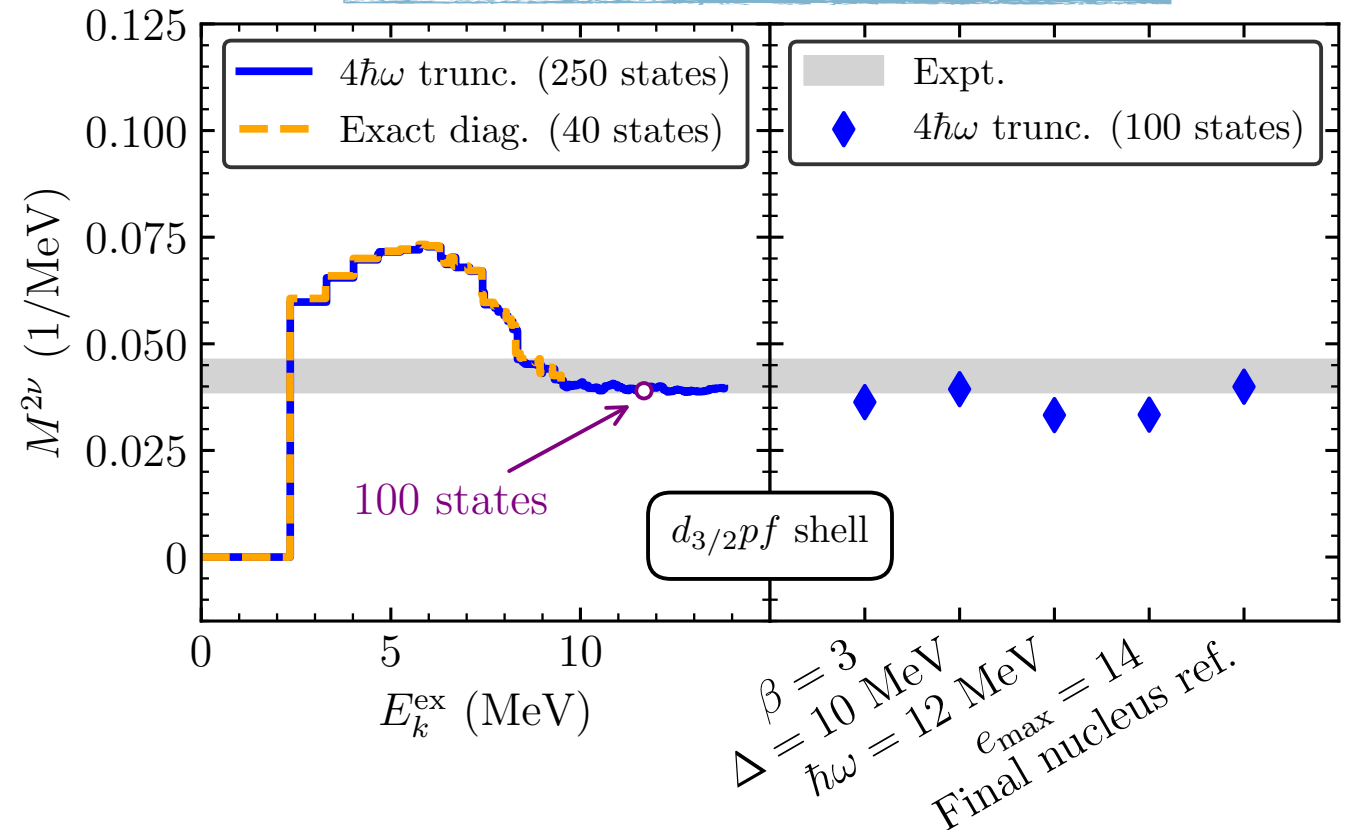
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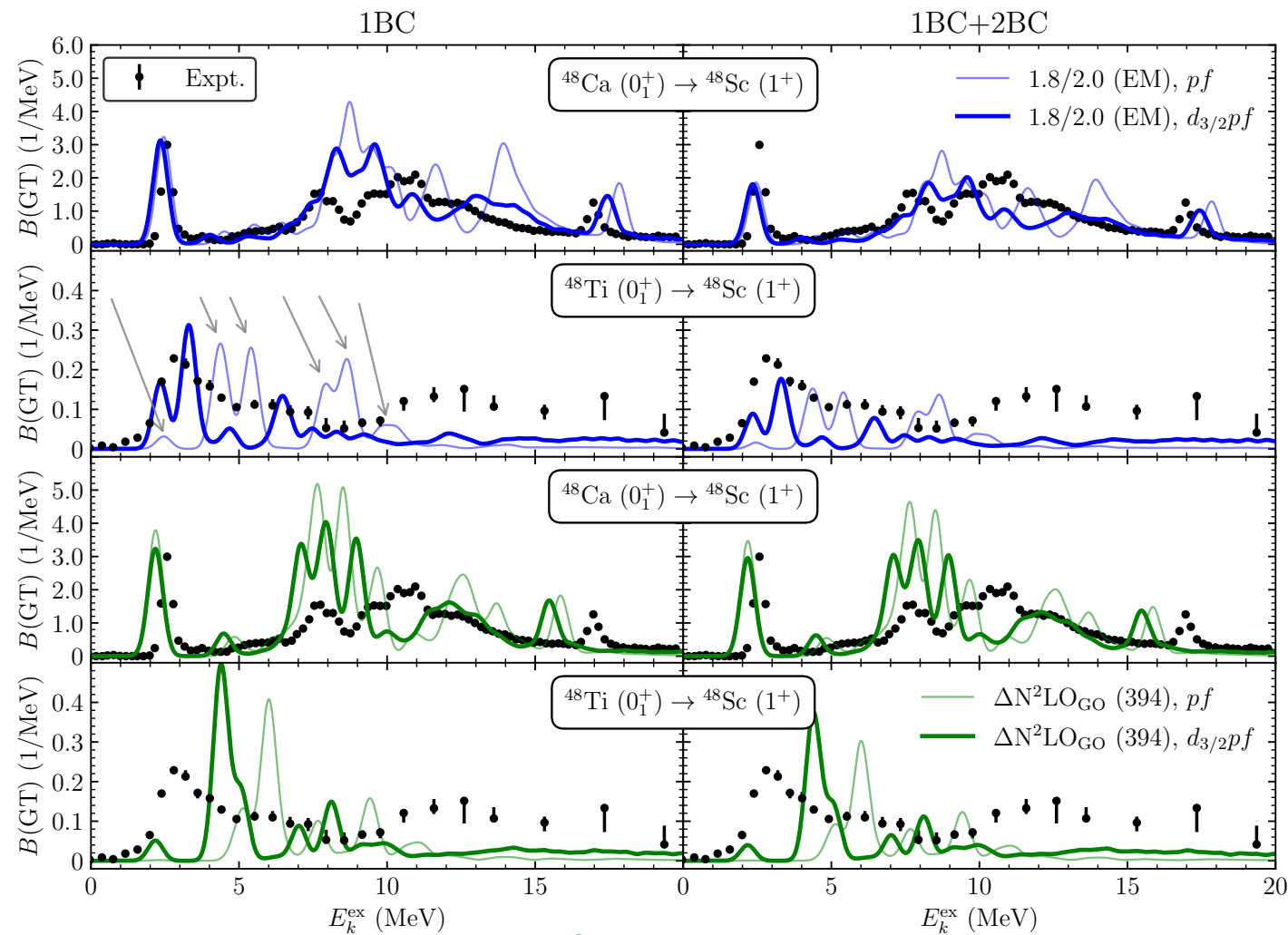
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BENCHMARKS WITH GAMOW-TELLER STRENGTHS

$$B(\text{GT}) = \frac{1}{2J+1} |\langle f || \mathbf{GT}^\pm || i \rangle|^2$$



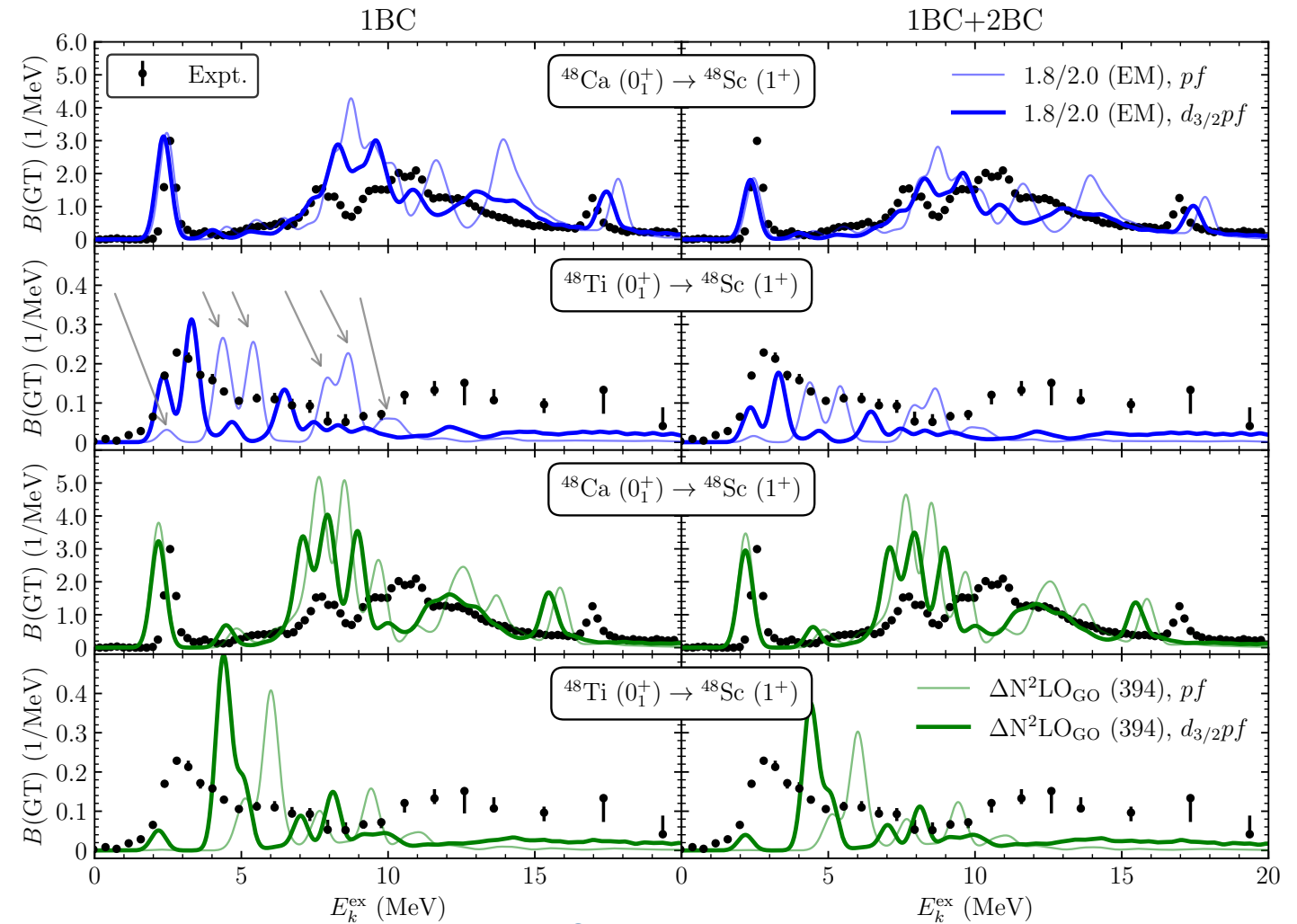
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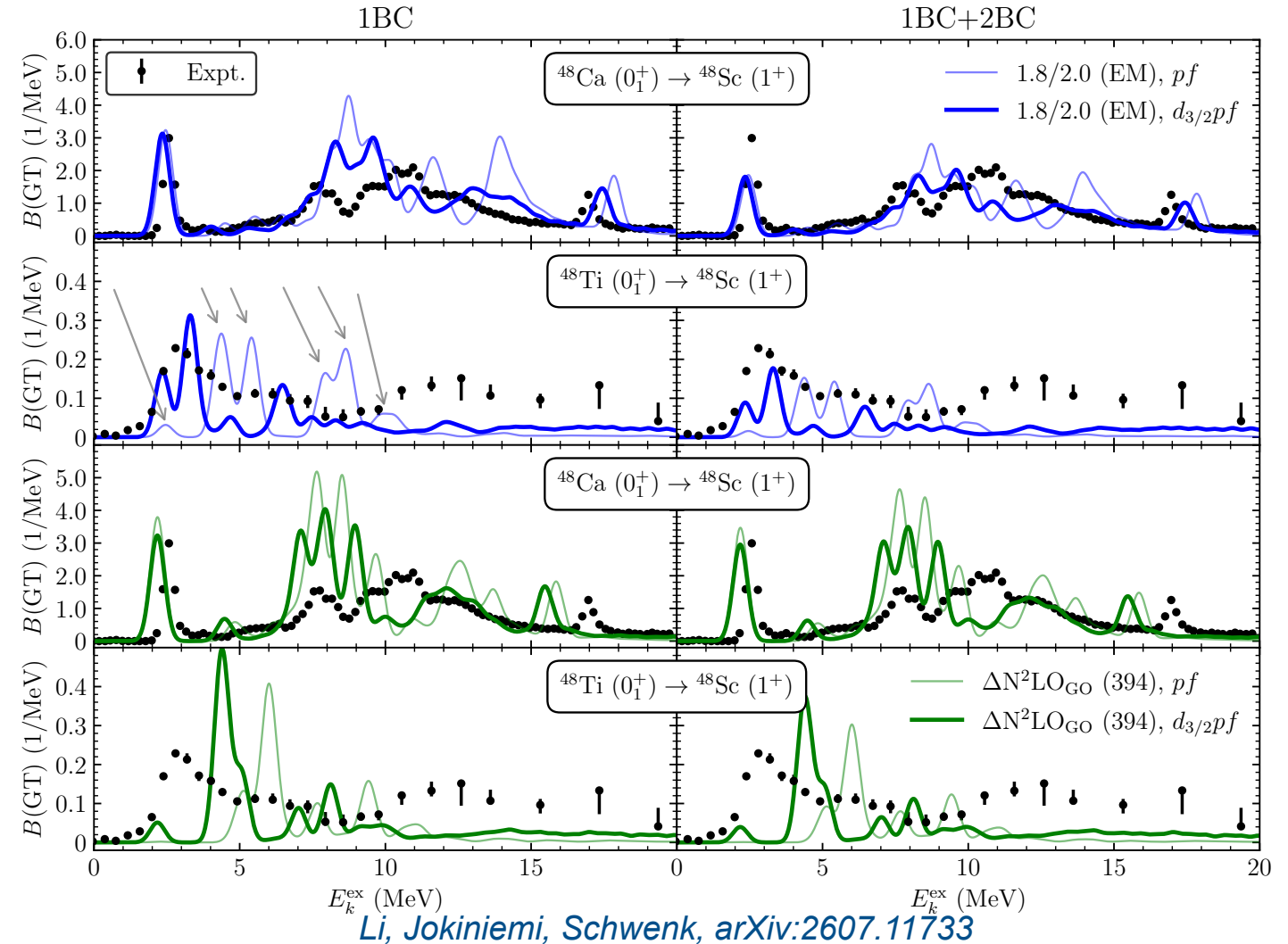


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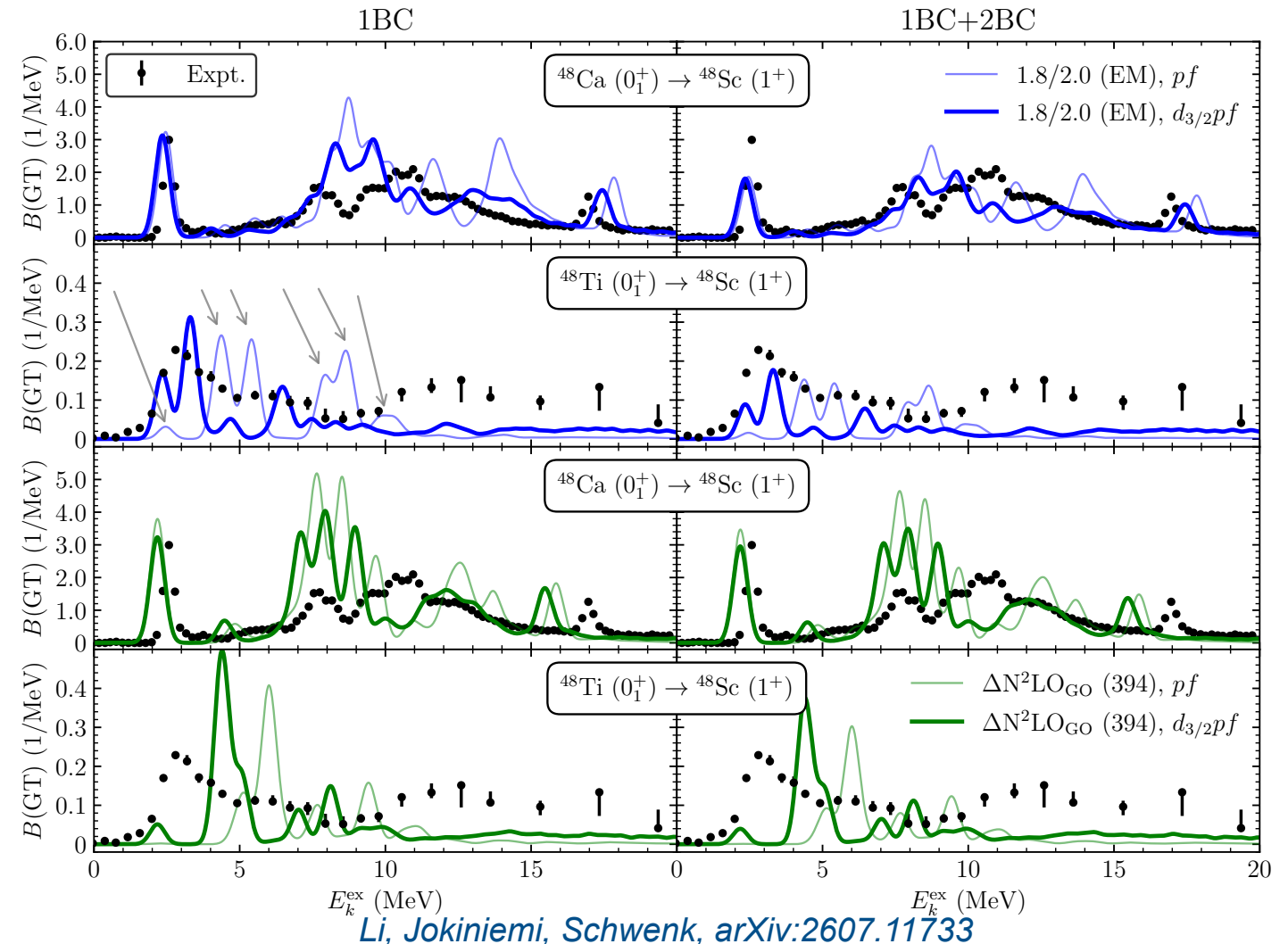
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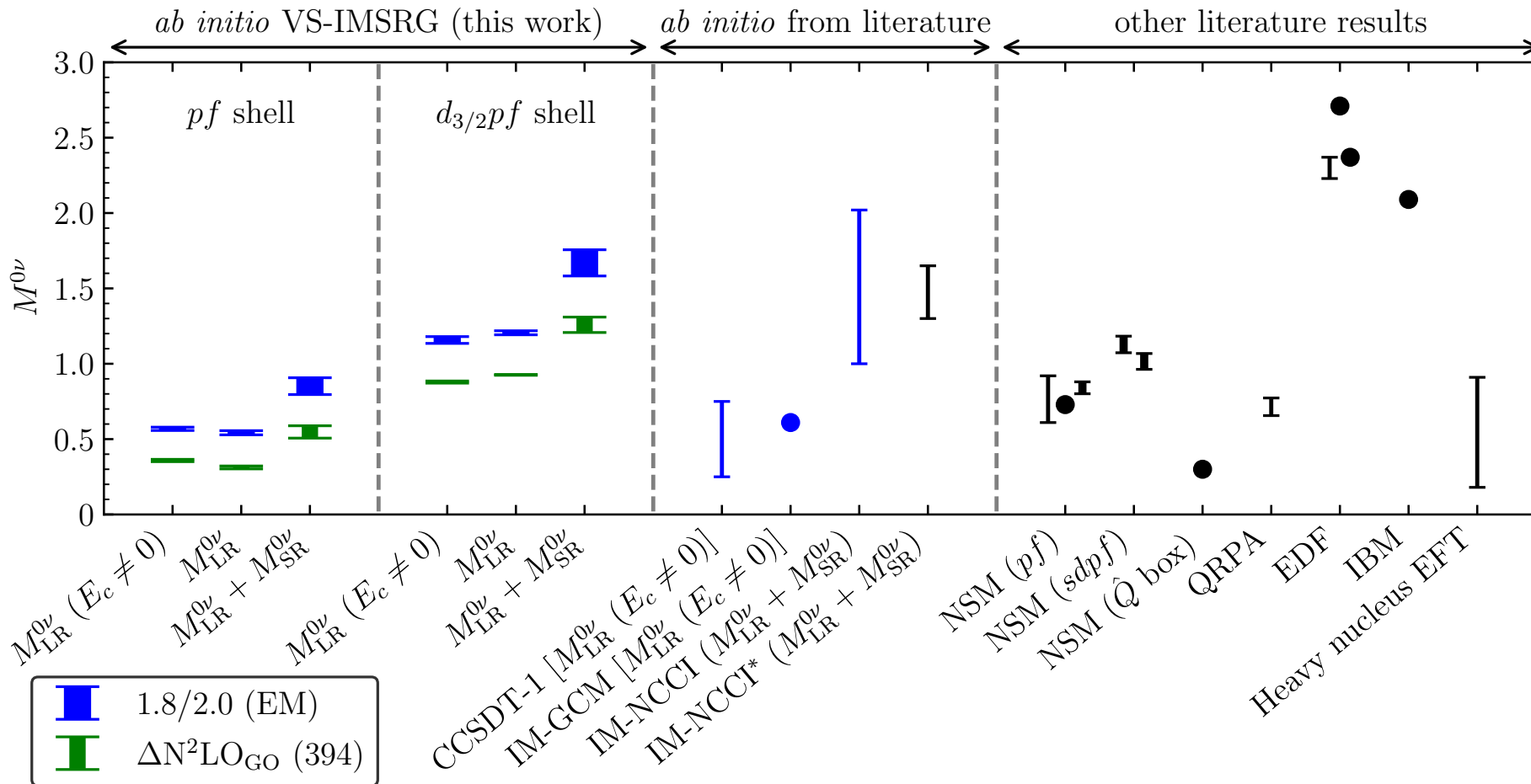
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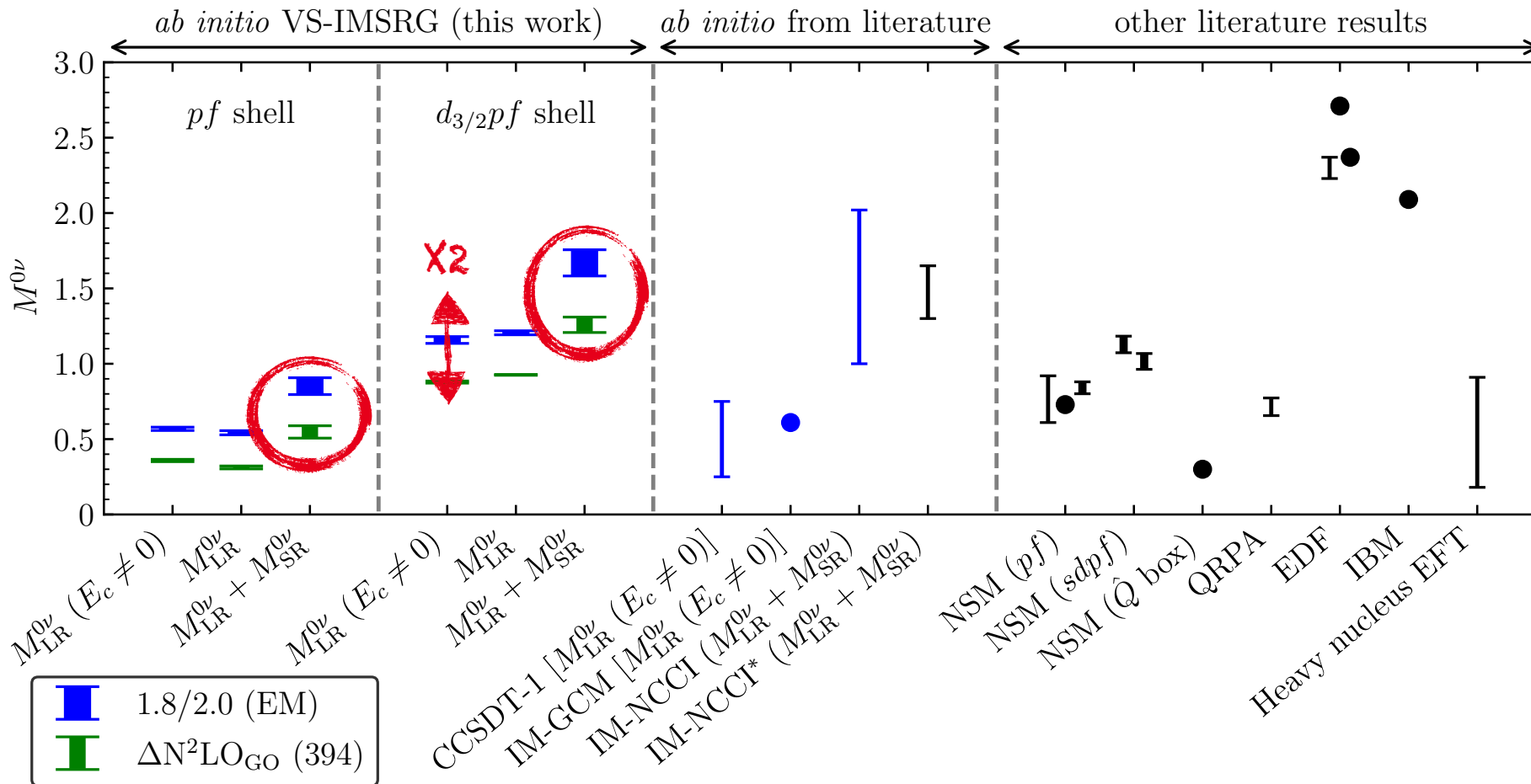


HOW DOES THIS AFFECT $0\nu\beta\beta$ DECAY?



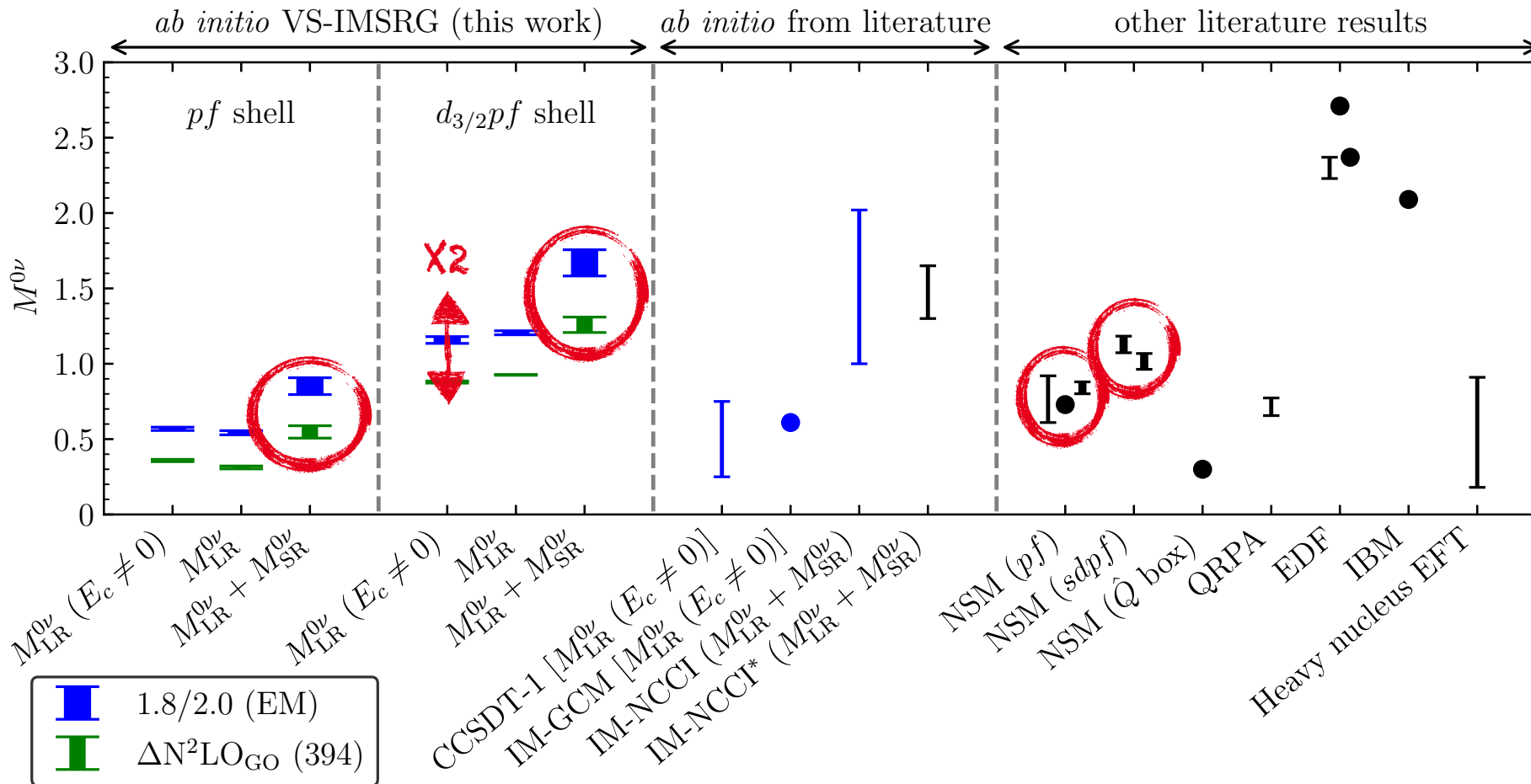
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Li, Jokiniemi, Schwenk, [arXiv:2607.11733](https://arxiv.org/abs/2607.11733)

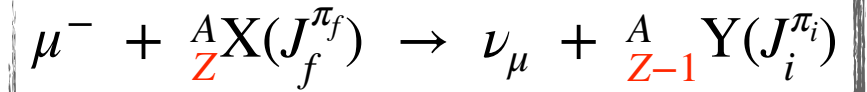
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Li, Jokiniemi, Schwenk, arXiv:2607.11733

HOW CAN WE PROBE THE WEAK CURRENT AT HIGH MOMENTUM TRANSFER?

MUON CAPTURE AS A PROBE OF $0\nu\beta\beta$ DECAY



Eur. Phys. J. C (2024) 84:1188
<https://doi.org/10.1140/epjc/s10052-024-13470-6>

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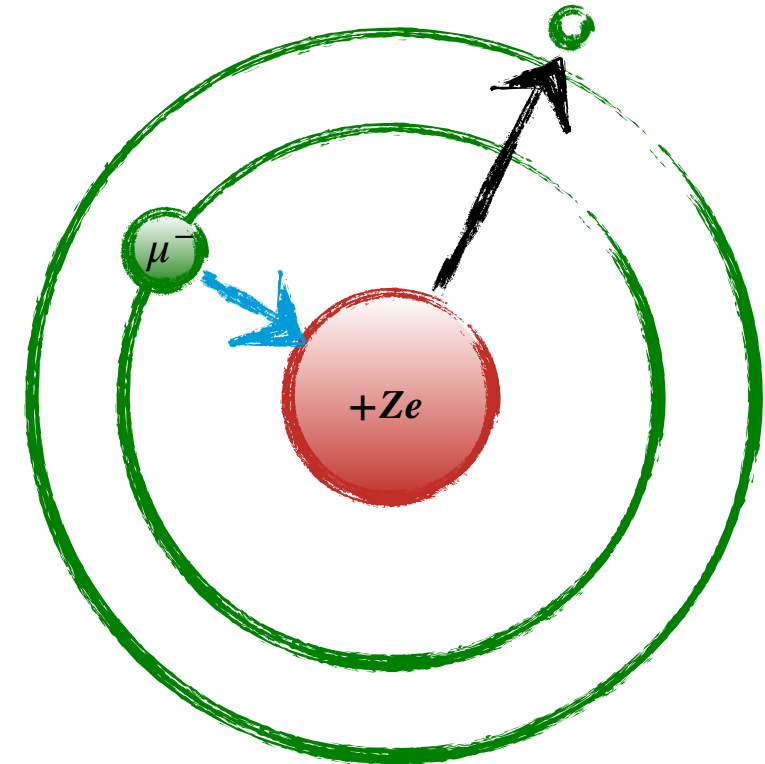
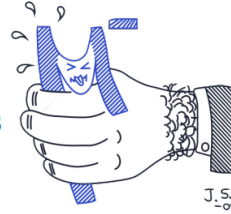


Regular Article

Experimental Physics

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$$\mu^- + {}^A_Z X(J_f^{\pi_f}) \rightarrow \nu_\mu + {}^A_{Z-1} Y(J_i^{\pi_i})$$

$$q_{\text{OMC}} \approx m_\mu + E_i - E_f \approx 100 \text{ MeV} \approx q_{0\nu\beta\beta}$$

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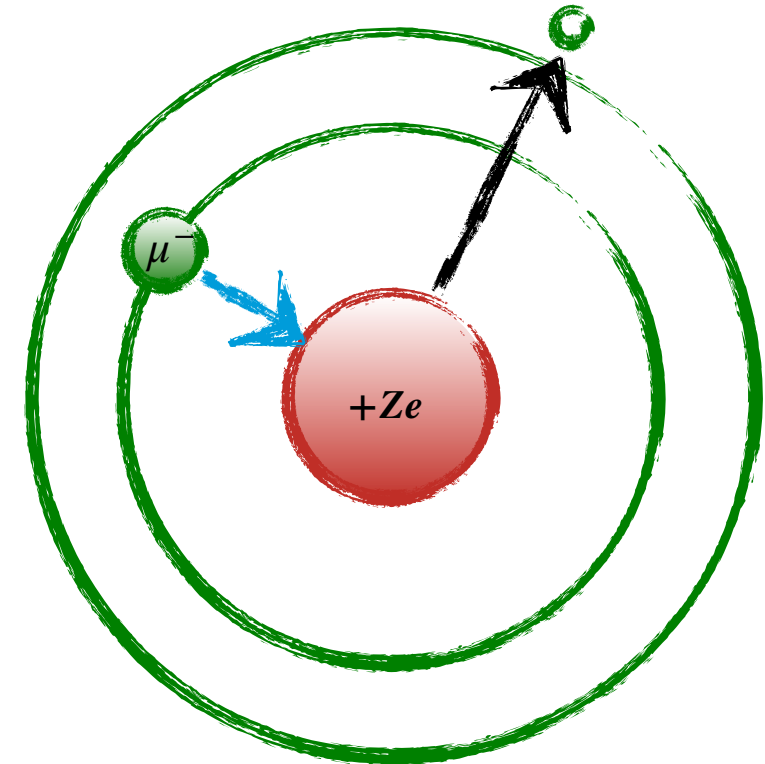
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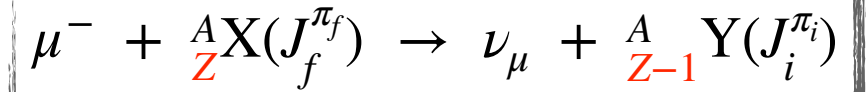
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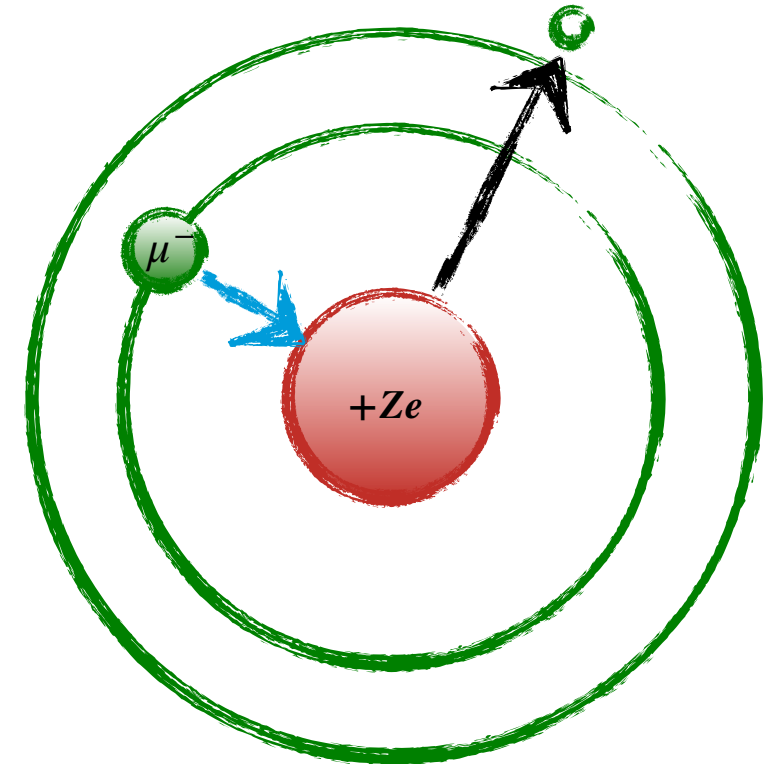
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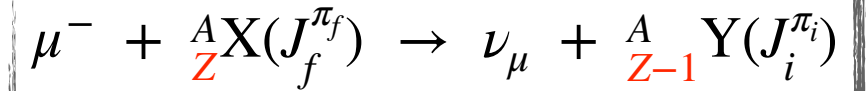


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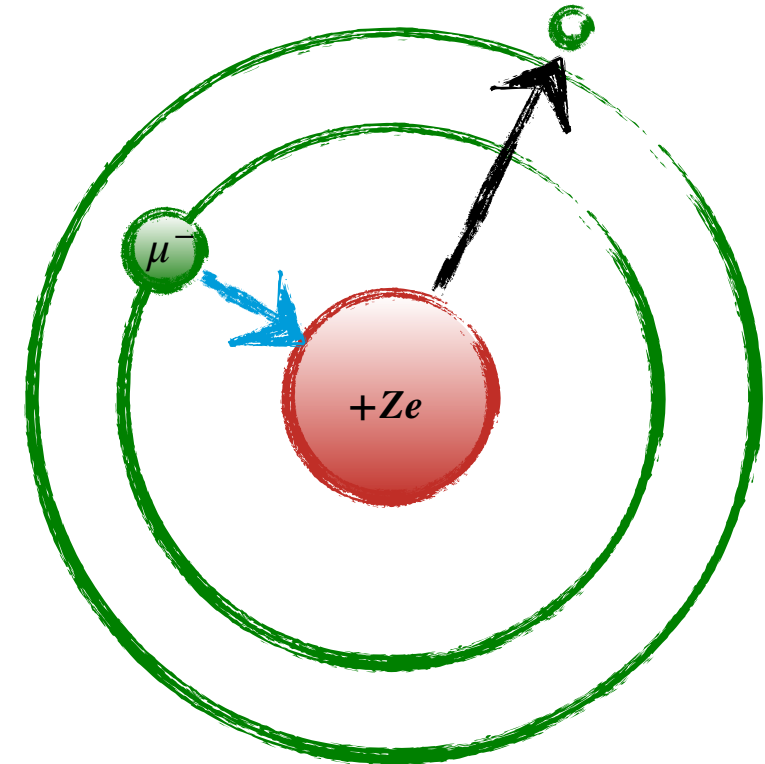
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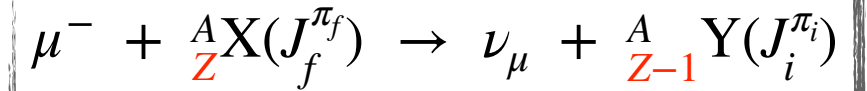


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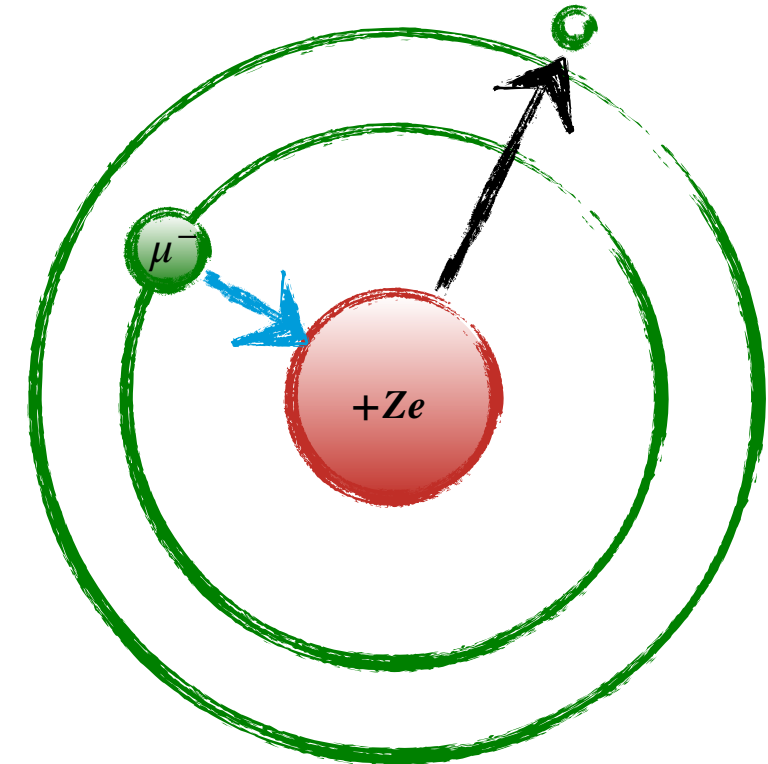
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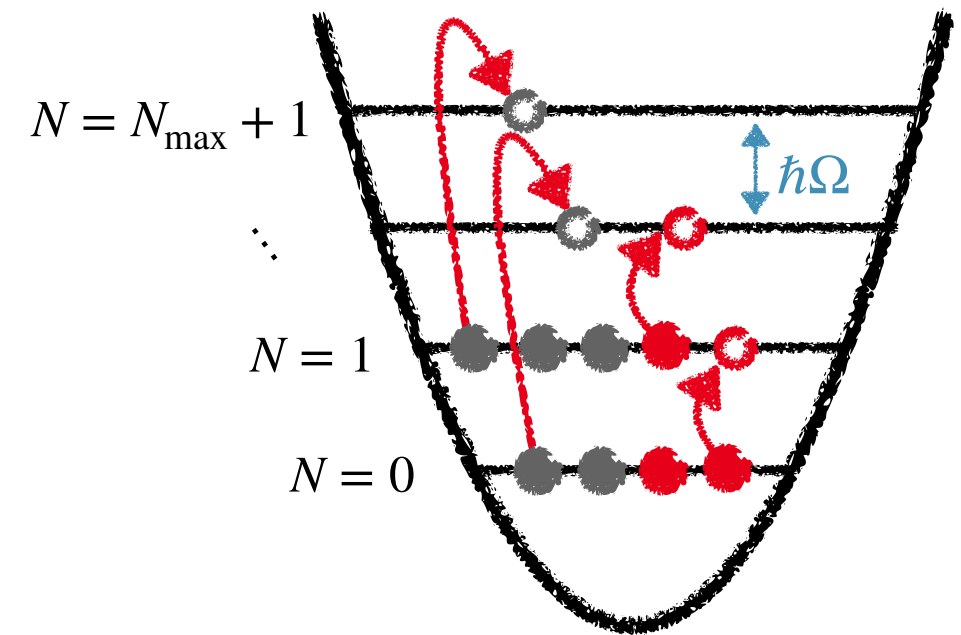


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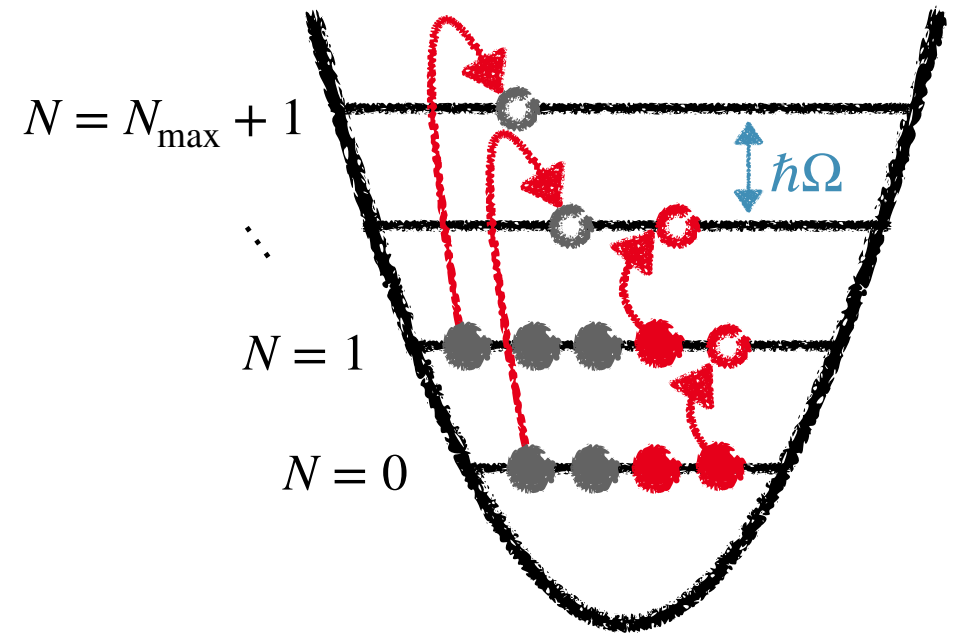
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- Solve the nuclear many-body problem

$$H^{(A)}\Psi^{(A)}(\mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_A) = E^{(A)}\Psi^{(A)}(\mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_A)$$



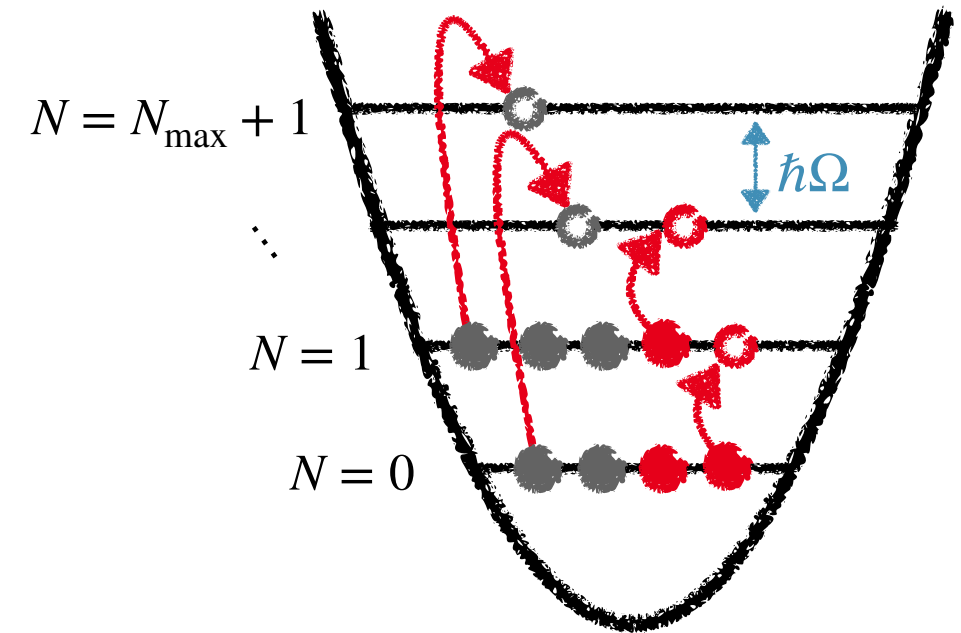
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- **Two- (NN)** and **three-body (3N)** forces from χ EFT:

$$H^{(A)} = \sum_{i=1}^A \frac{p_i^2}{2m} + \sum_{i<j=1}^A V_{ij}^{\text{NN}}(\mathbf{r}_i - \mathbf{r}_j) + \sum_{i<j<k=1}^A V_{ijk}^{\text{3N}}$$



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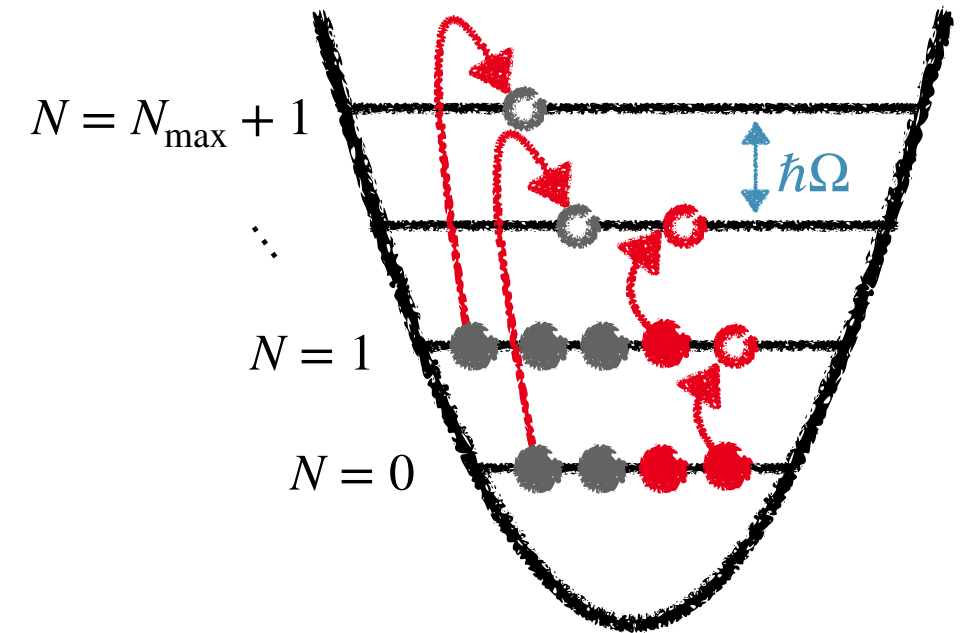
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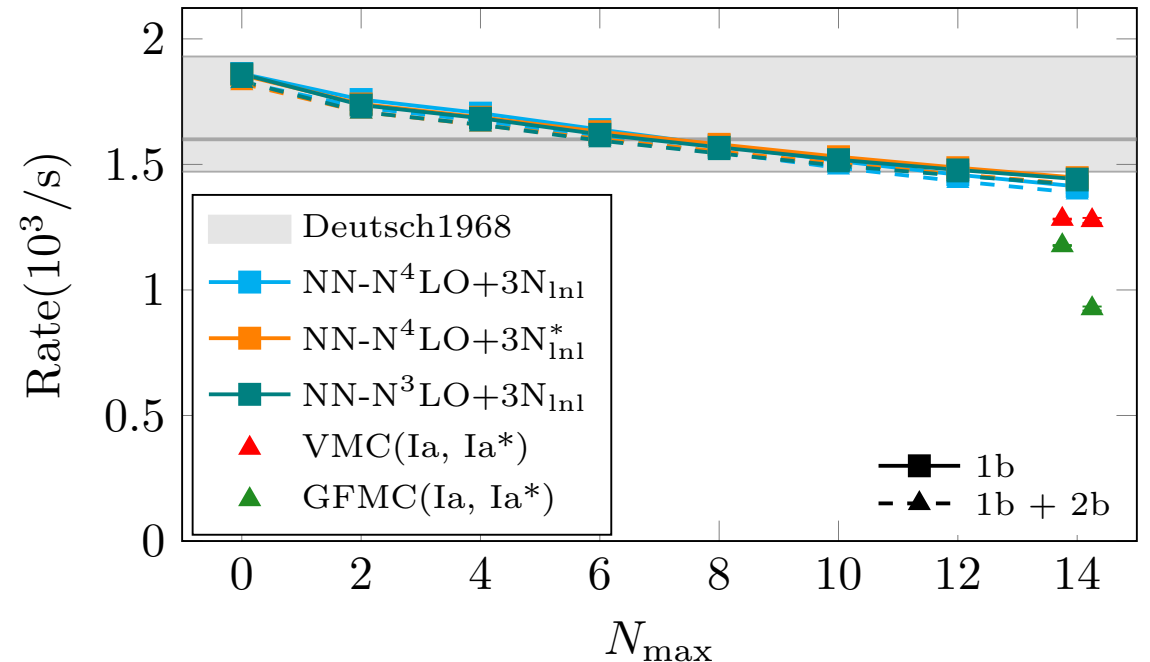
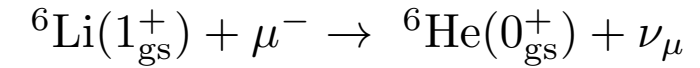
- Expansion in Harmonic Oscillator (HO) basis:

$$\Psi^{(A)} = \sum_{N=0}^{N_{\max}} \sum_j = c_{Nj} \Phi_{Nj}^{\text{HO}}(\mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_A)$$



MUON CAPTURE ON ${}^6\text{Li}$

$$W(i \rightarrow f) = 2\pi \langle |\mathcal{M}_{i \rightarrow f}|^2 \rangle_{\text{av}} q^2 \frac{dq}{dE_f}$$

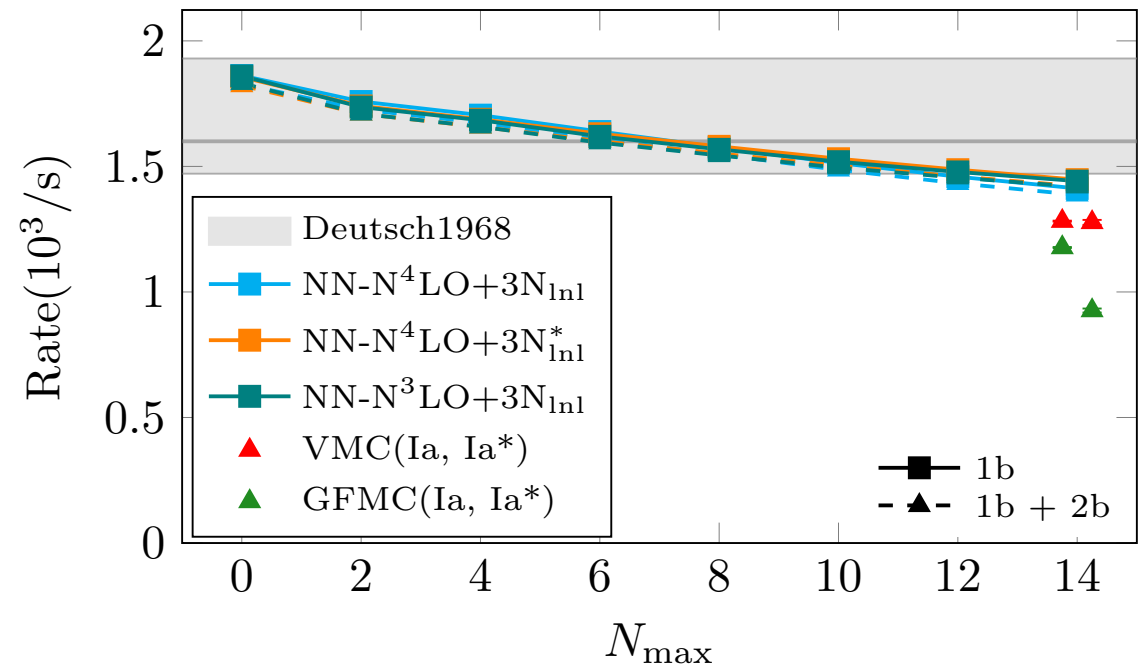
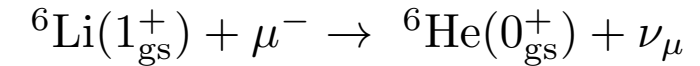


*LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C
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- No-core shell model slightly underestimates the experiment



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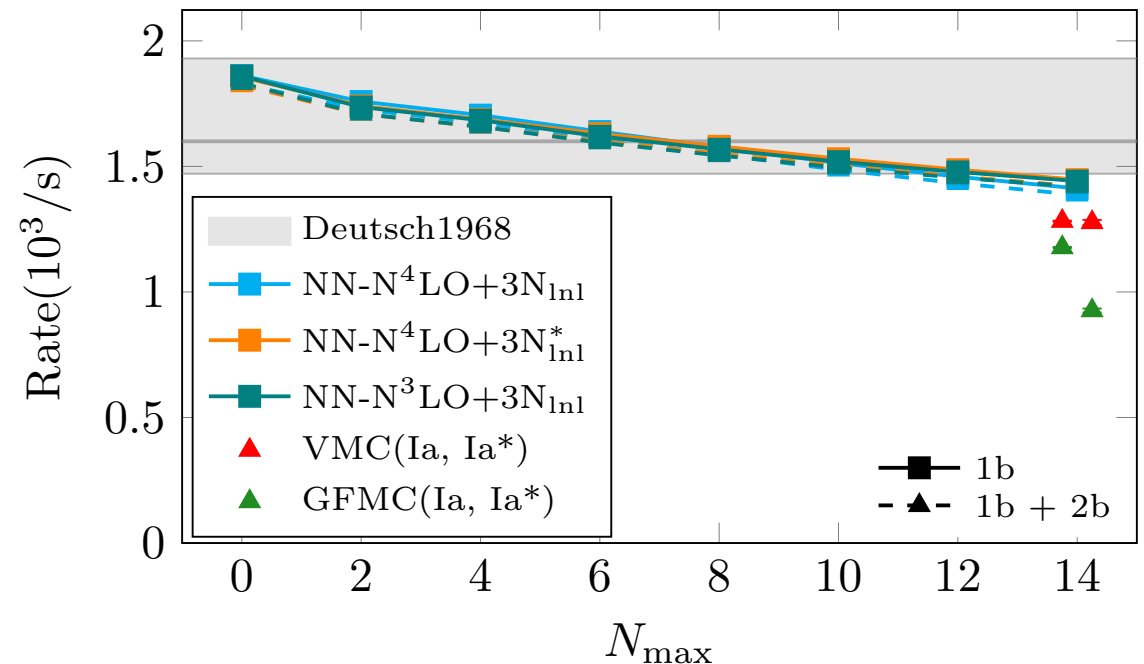
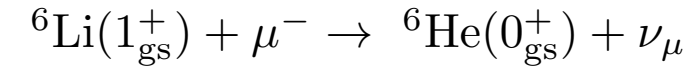
MUON CAPTURE ON ${}^6\text{Li}$

$$W(i \rightarrow f) = 2\pi \langle |\mathcal{M}_{i \rightarrow f}|^2 \rangle_{\text{av}} q^2 \frac{dq}{dE_f}$$

- No-core shell model slightly underestimates the experiment
- Results consistent with other *ab initio* methods:

Variational Monte Carlo (VMC) and
Green's Function Monte Carlo (GFMC)

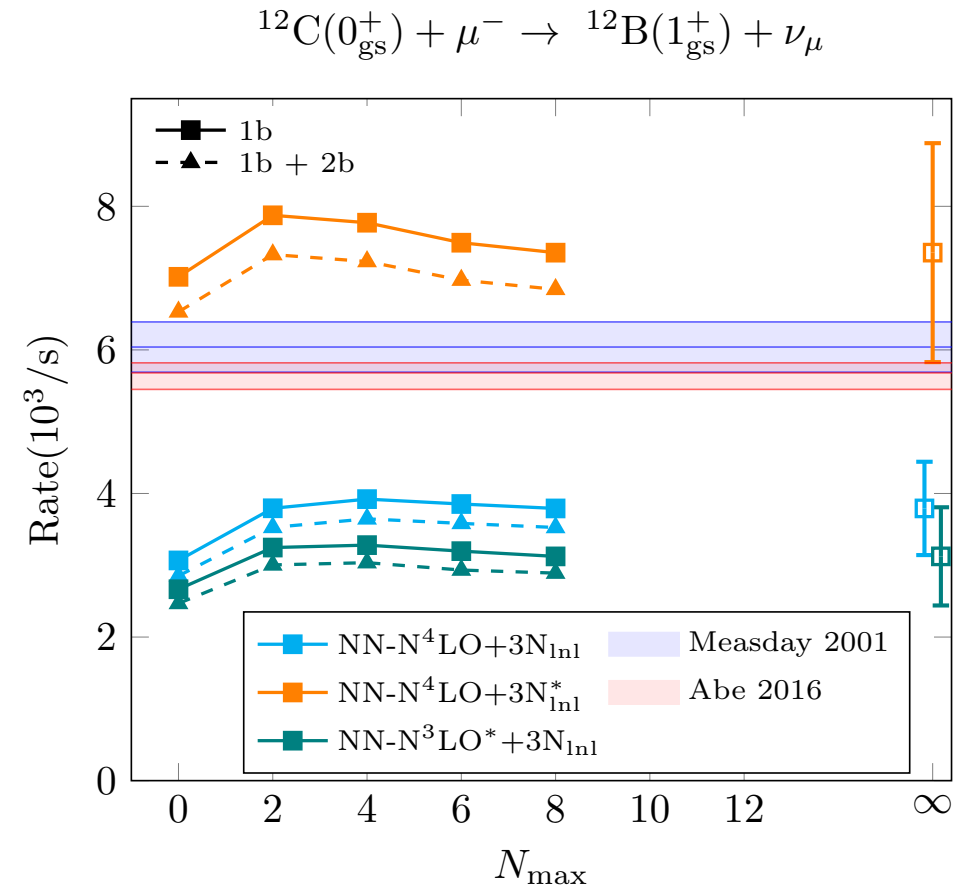
G. B. King et al., Phys. Rev. C 105, L042501 (2022)



LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C 109, 065501 (2024)

MUON CAPTURE ON ^{12}C

$$W(i \rightarrow f) = 2\pi \langle |\mathcal{M}_{i \rightarrow f}|^2 \rangle_{\text{av}} q^2 \frac{dq}{dE_f}$$

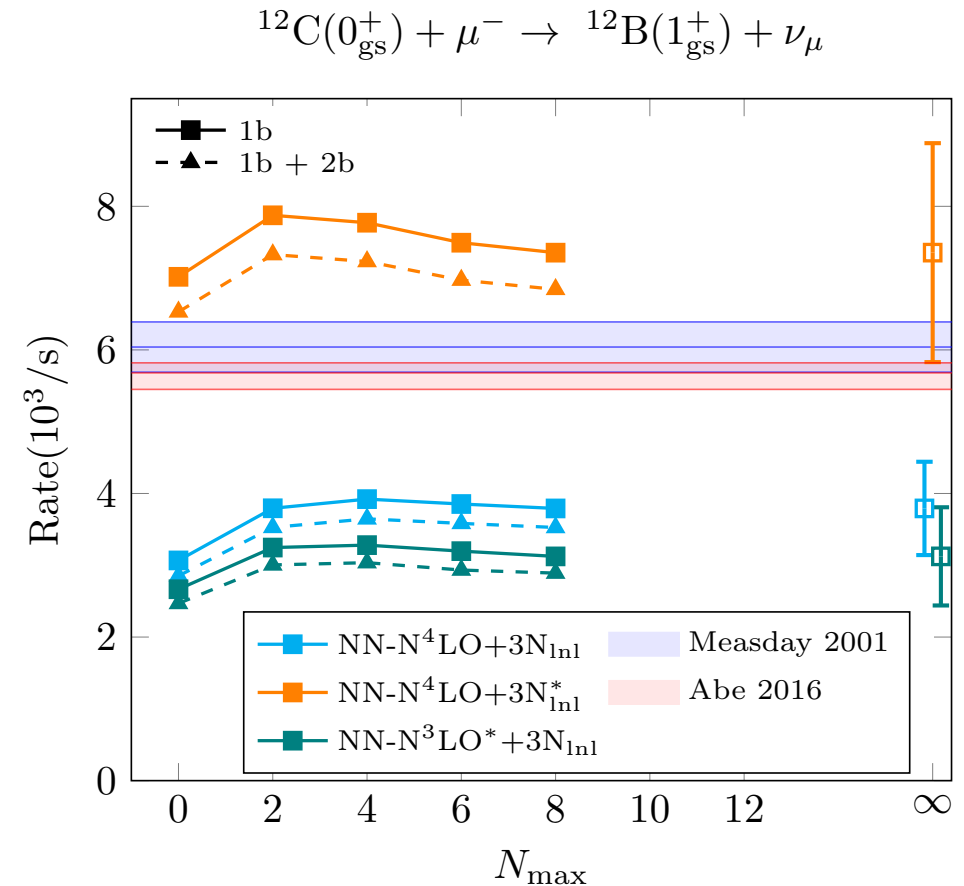


LJ, P. Navrátil, J. Kotila, K. Kravvaris, *Phys. Rev. C*
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- Significant interaction dependence

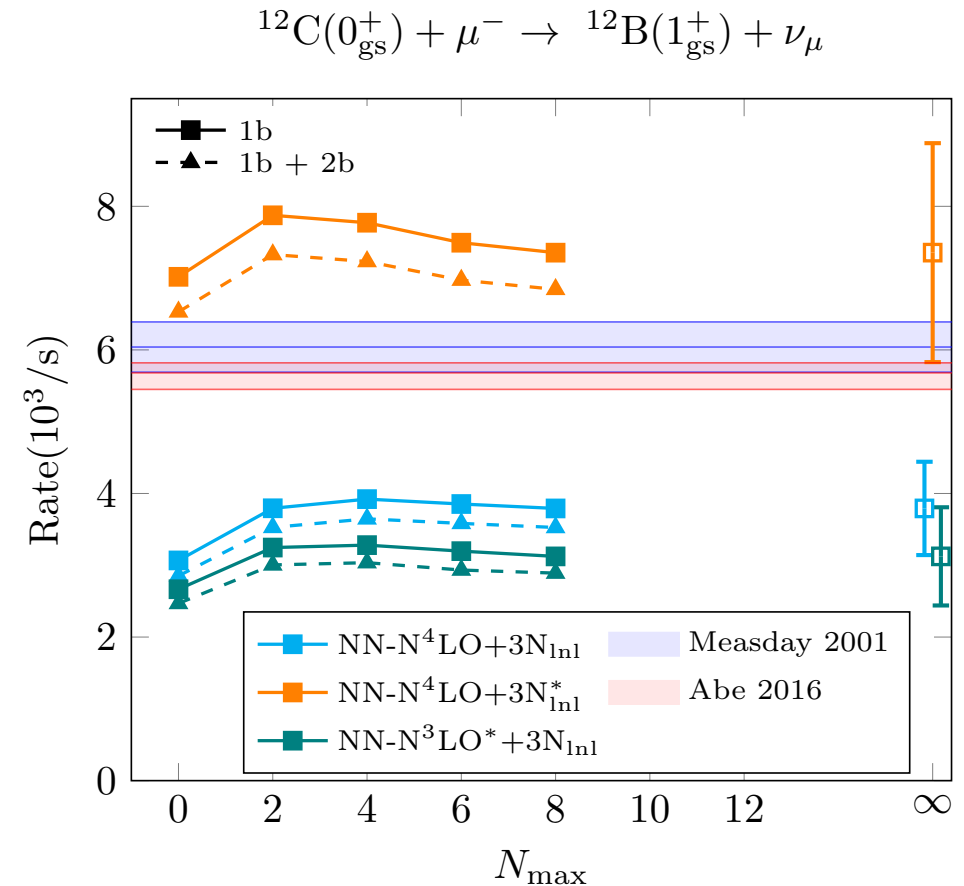


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 - The $\text{NN} - \text{N}^4\text{LO} + 3\text{N}_{\text{Inl}}^*$ interaction with the **subleading 3N term (E7)** most consistent with experiments
Girlanda, Kievsky, Viviani, Phys. Rev. C 84, 014001 (2011)

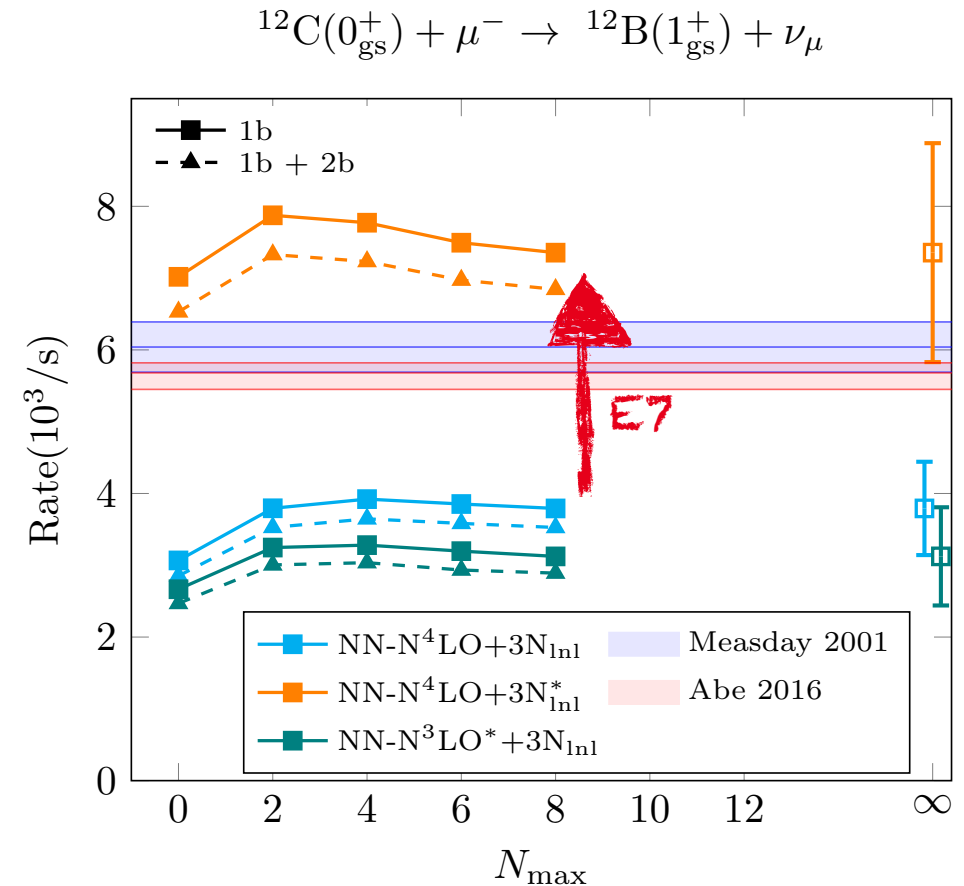


LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C 109, 065501 (2024)

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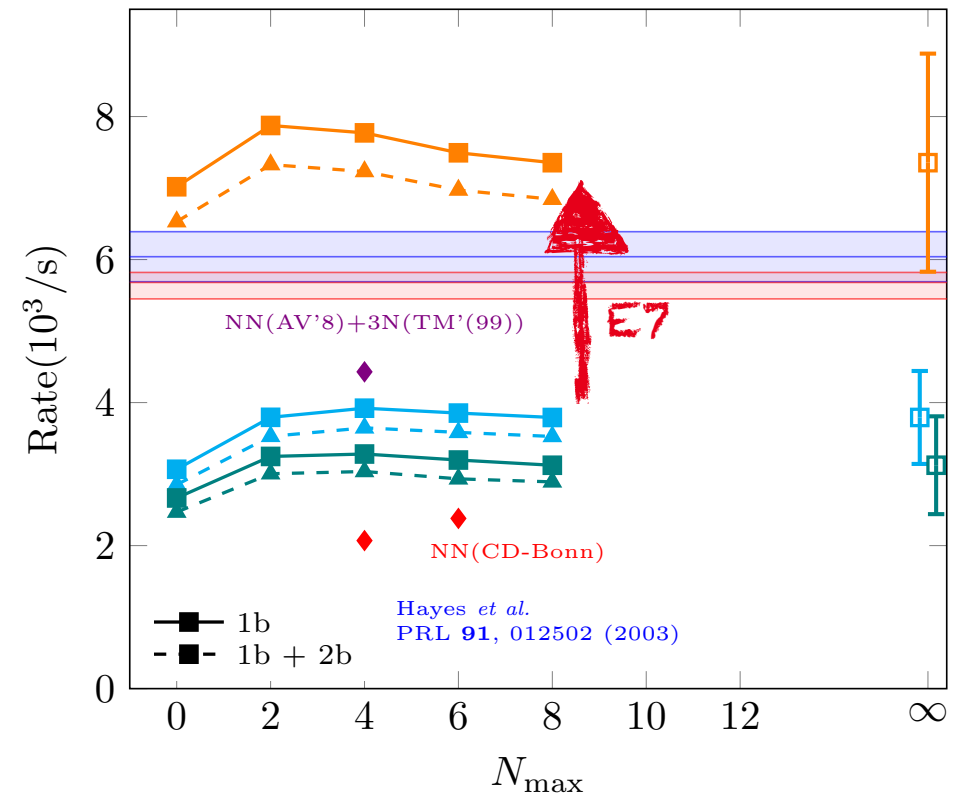
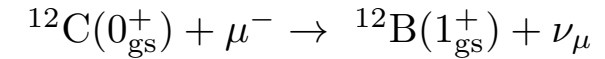


LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C 109, 065501 (2024)

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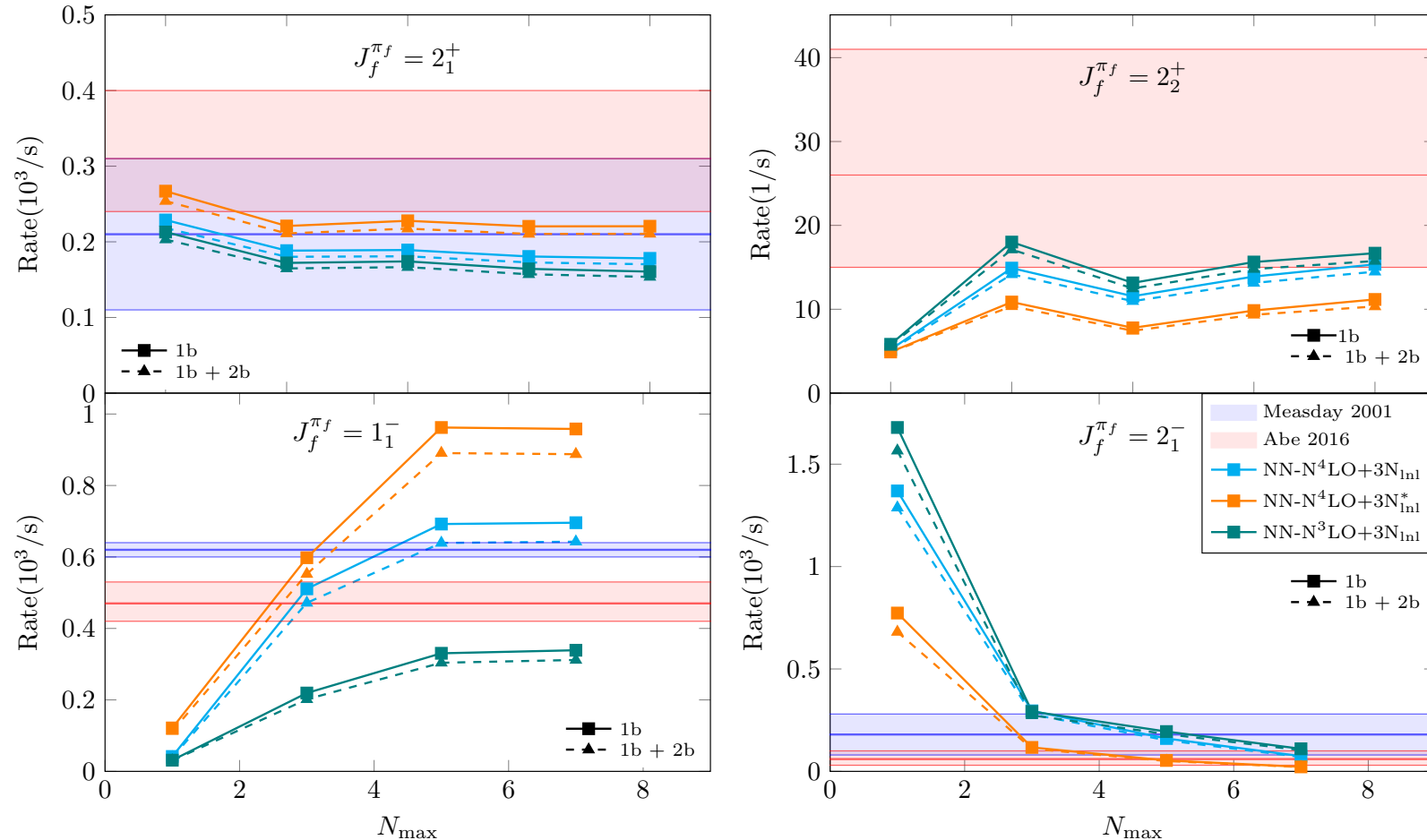
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Girlanda, Kievsky, Viviani, Phys. Rev. C 84, 014001 (2011)
- **3-body forces essential** to reproduce the measured rate



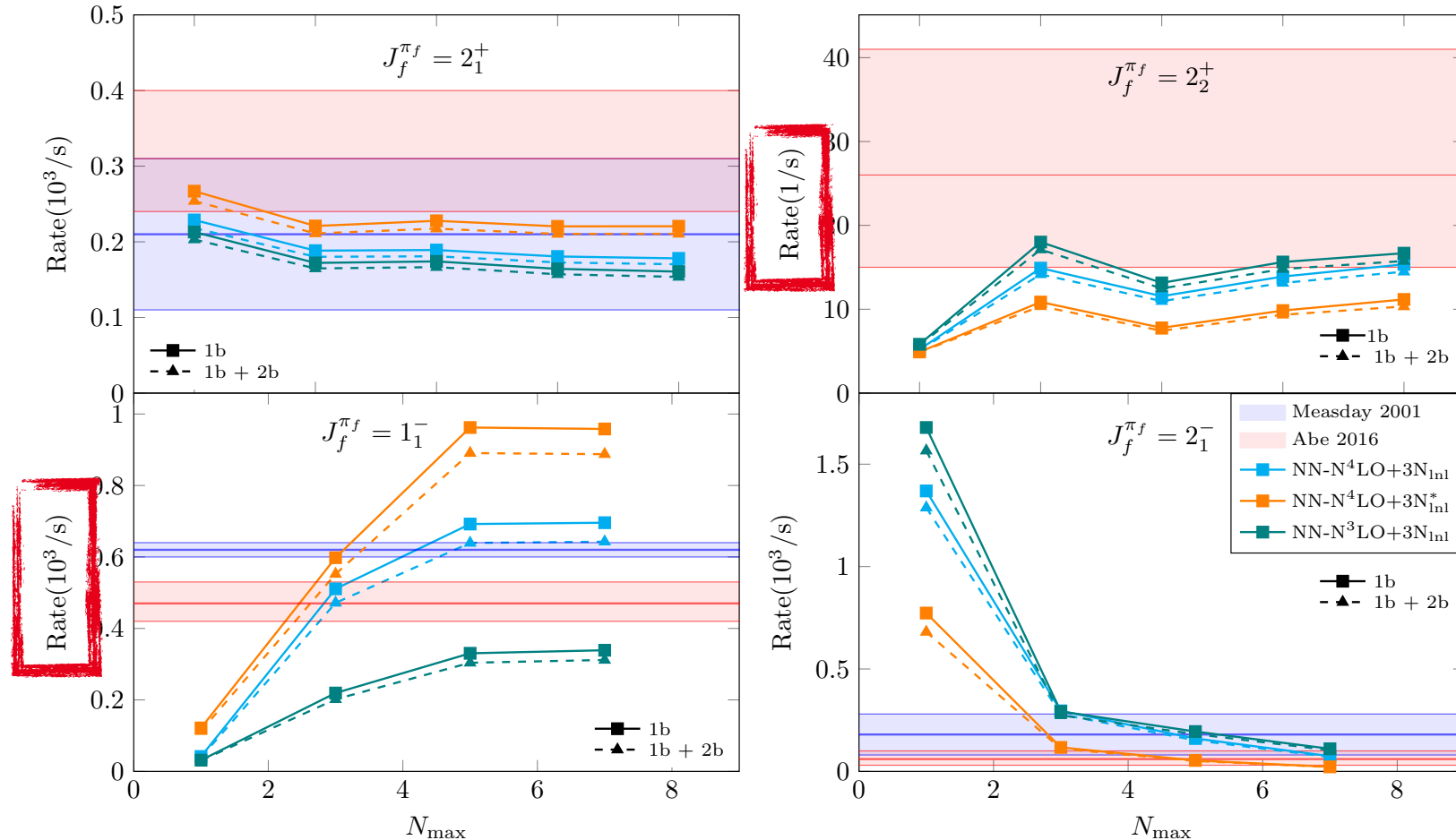
LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C 109, 065501 (2024)

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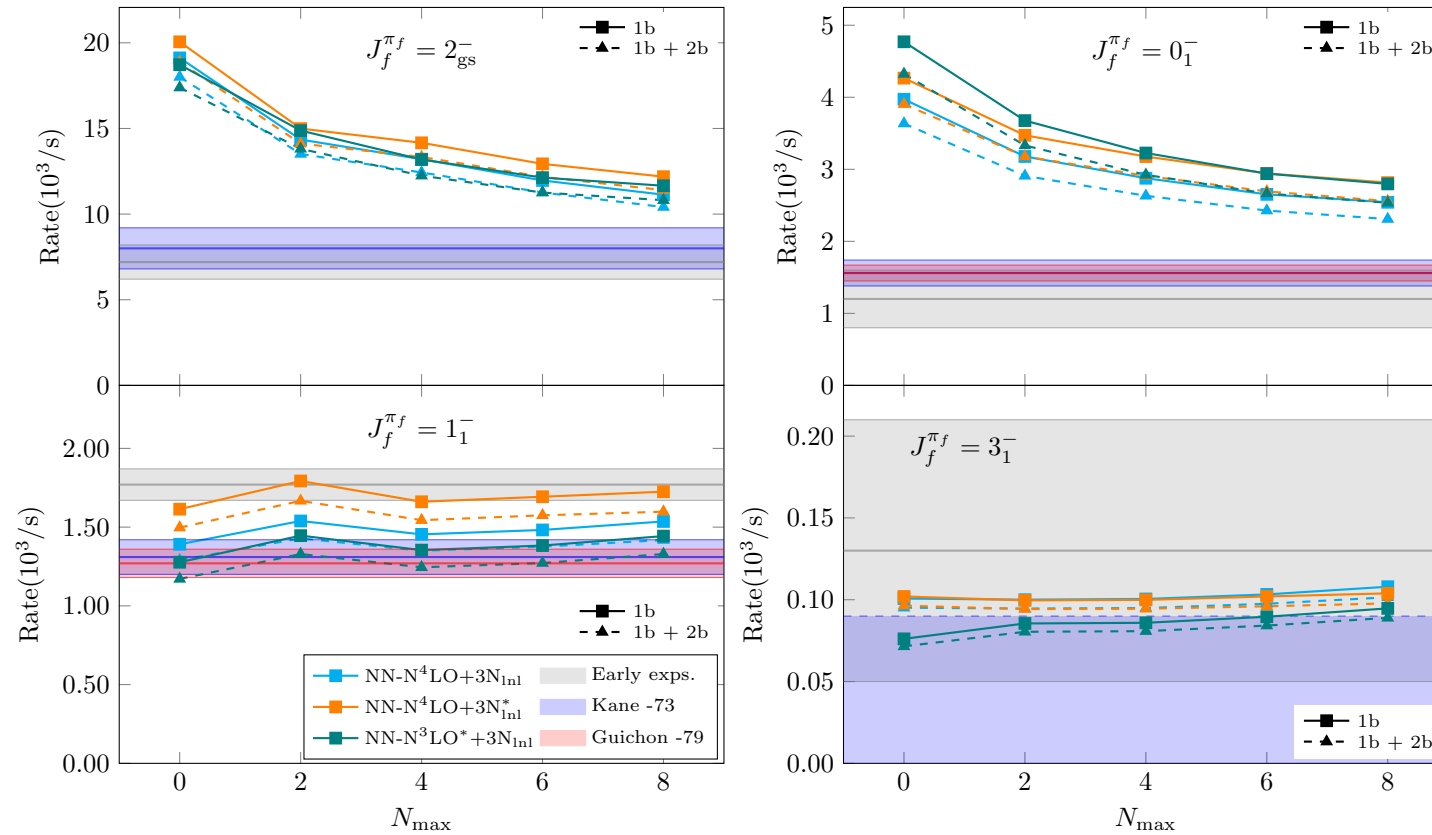
LJ, P. Navrátil, J. Kotila, K. Kravvaris, *Phys. Rev. C* 109, 065501 (2024)

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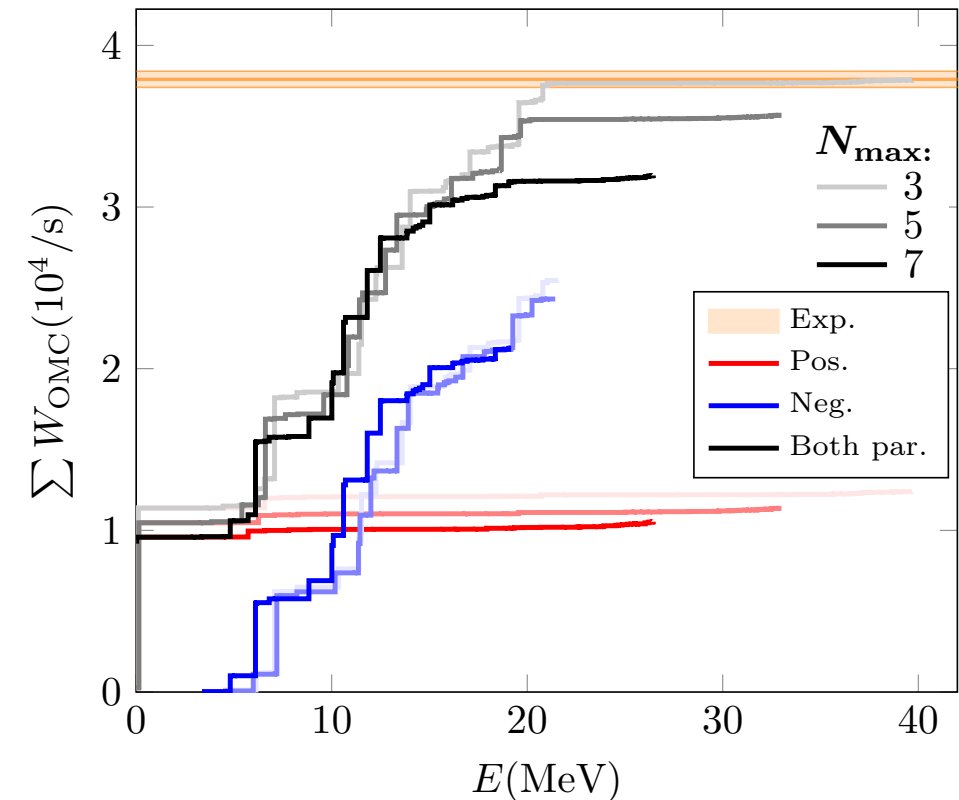
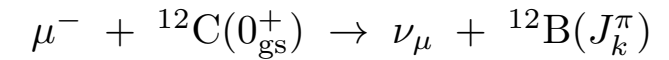
MUON CAPTURE ON ^{16}O



LJ, P. Navrátil, J. Kotila, K. Kravvaris, *Phys. Rev. C* 109, 065501 (2024)

TOTAL MUON CAPTURE RATES

$$W_{\text{tot.}} = \sum_f W(i \rightarrow f)$$

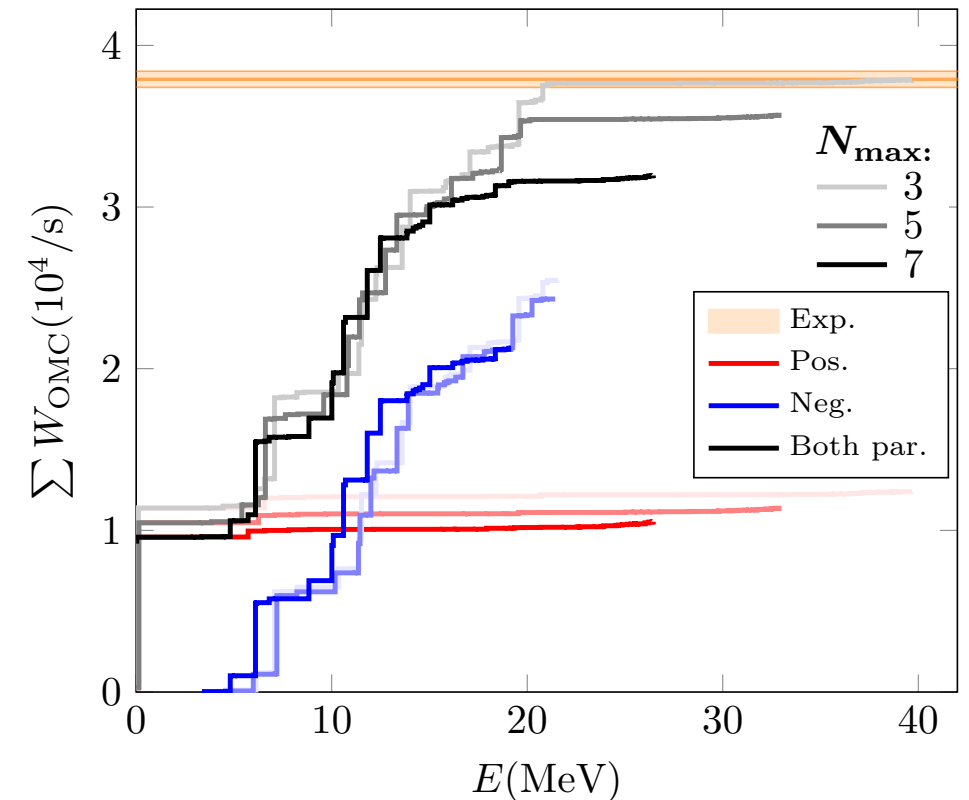
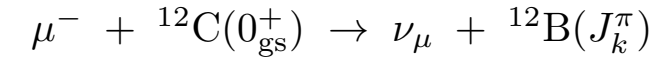


LJ, P. Navrátil, J. Kotila, K. Kravvaris, *Phys. Rev. C*
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- Rates obtained by summing over **~50 final states of each parity**

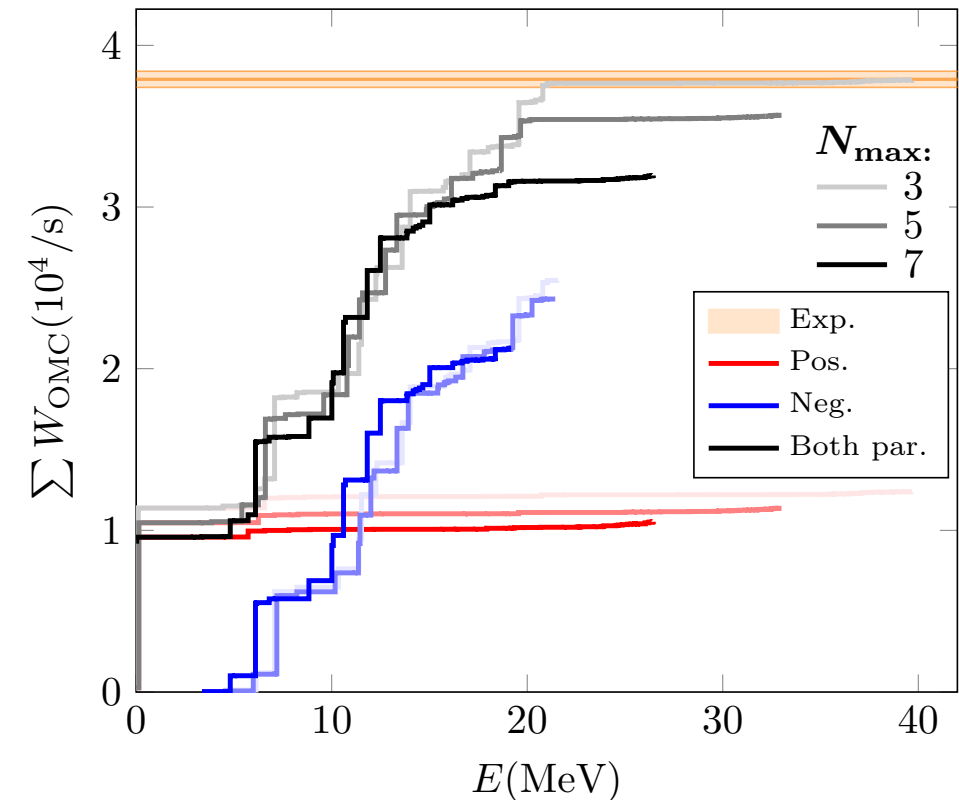
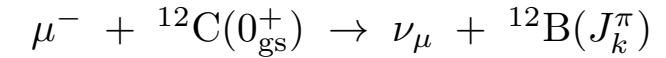


LJ, P. Navrátil, J. Kotila, K. Kravvaris, *Phys. Rev. C*
109, 065501 (2024)

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$$W_{\text{tot.}} = \sum_f W(i \rightarrow f)$$

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- Summing up the rates up to ~20 MeV, we capture **~85% of the total rate** in both ^{12}C and ^{16}N

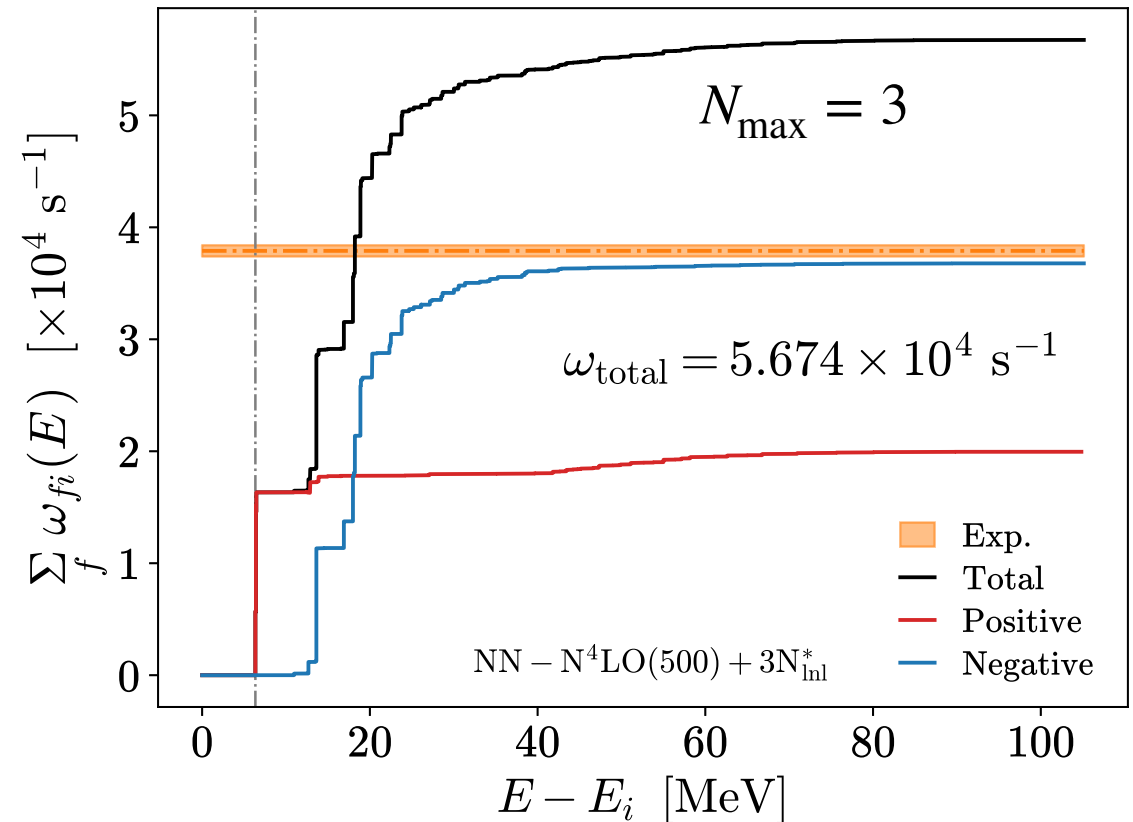


LJ, P. Navrátil, J. Kotila, K. Kravvaris, *Phys. Rev. C*
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- **Better estimation of the total rates using the Lanczos strength function method underway**



*D. Araujo Najera, M. Gennari, LJ, M. Drissi,
P. Navrátil, work in progress*

SUMMARY

- Next-generation $0\nu\beta\beta$ -decay experiments likely to fully cover the inverted-hierarchy band of neutrino masses
- Muon capture a good probe for high-momentum electroweak currents
- Correlations with different observables help constrain the $0\nu\beta\beta$ -decay matrix elements
- Important correlations were missing from *ab initio* calculations of $\beta\beta$ decays of $^{48}\text{Ca} \rightarrow$ *How about heavier cases?*

