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Exzellente Forschung für
Hessens Zukunft



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PROBING NEUTRINOLESS DOUBLE-BETA DECAY BY NUCLEAR OBSERVABLES

Lotta Jokiniemi

Institut für Kernphysik, Theoriezentrum, TU Darmstadt

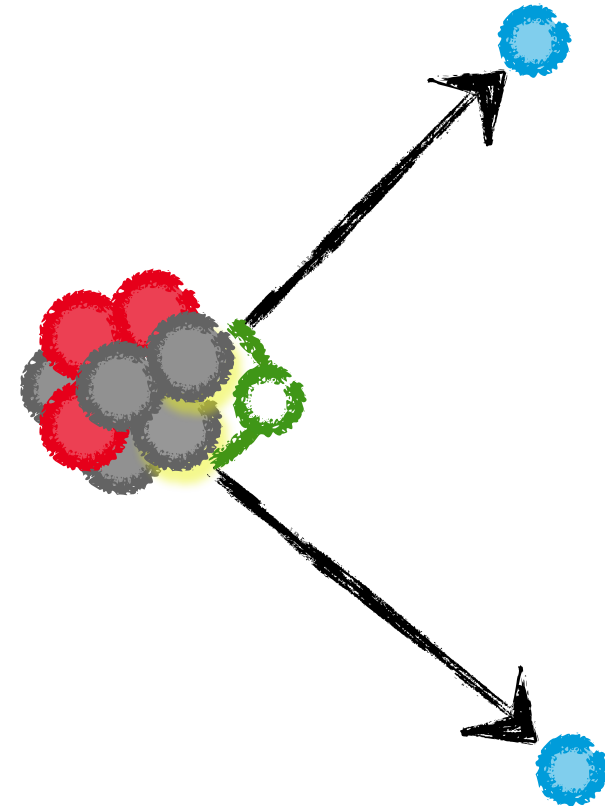


Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

14th International Spring Seminar on Nuclear Physics, Ischia, May 5-9, 2025

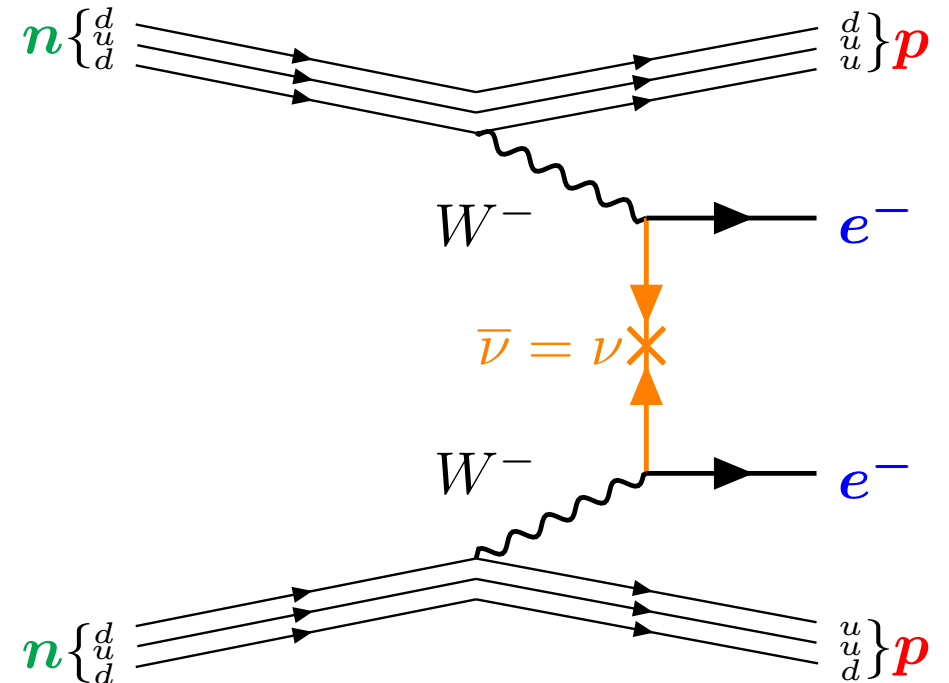
OUTLINE

- 1** Introduction to double-beta decay
- 2** Charge-exchange reactions as a probe
- 3** Muon capture as a probe
- 4** Summary and Outlook



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

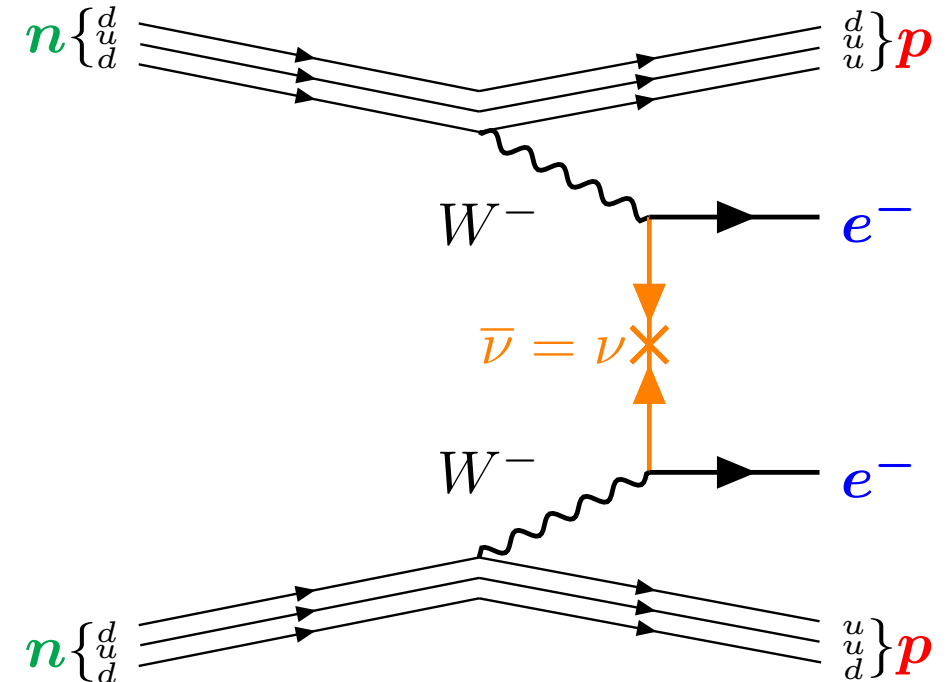
$$(A, Z) \rightarrow (A, Z + 2) + 2e^- + \cancel{2\nu_e}$$



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

- Violates lepton-number conservation

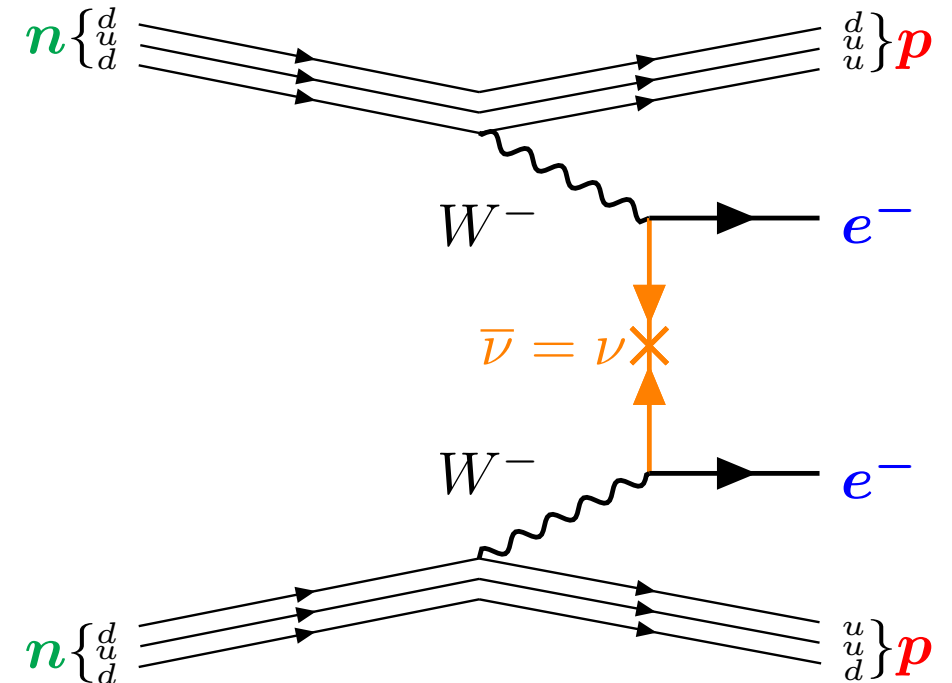
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NEUTRINOLESS DOUBLE-BETA ($0\nu\beta\beta$) DECAY

- Violates lepton-number conservation
- Requires that neutrinos are Majorana particles

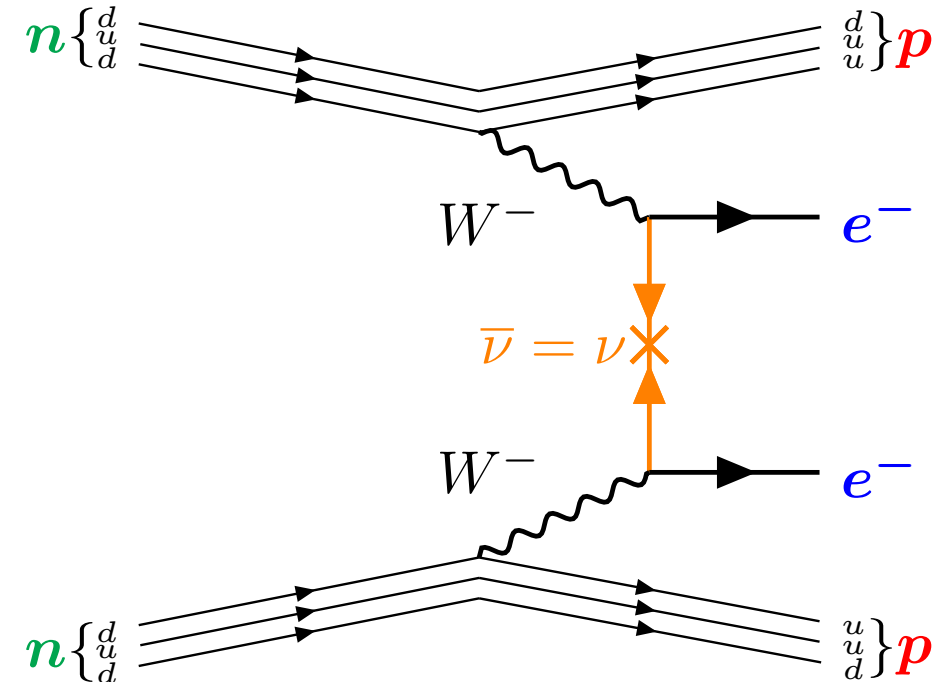
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- If observed, $t_{1/2}^{0\nu} \gtrsim 10^{25}$ years

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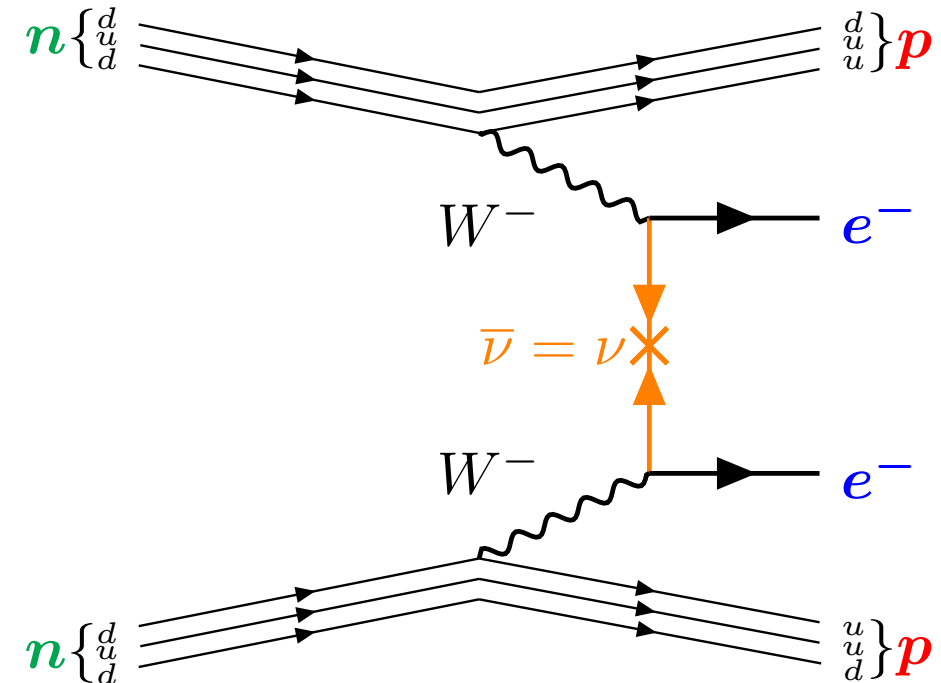


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($t_{1/2}^{2\nu} \approx 10^{20}$ years, Age of the Universe $\approx 10^{10}$ years)

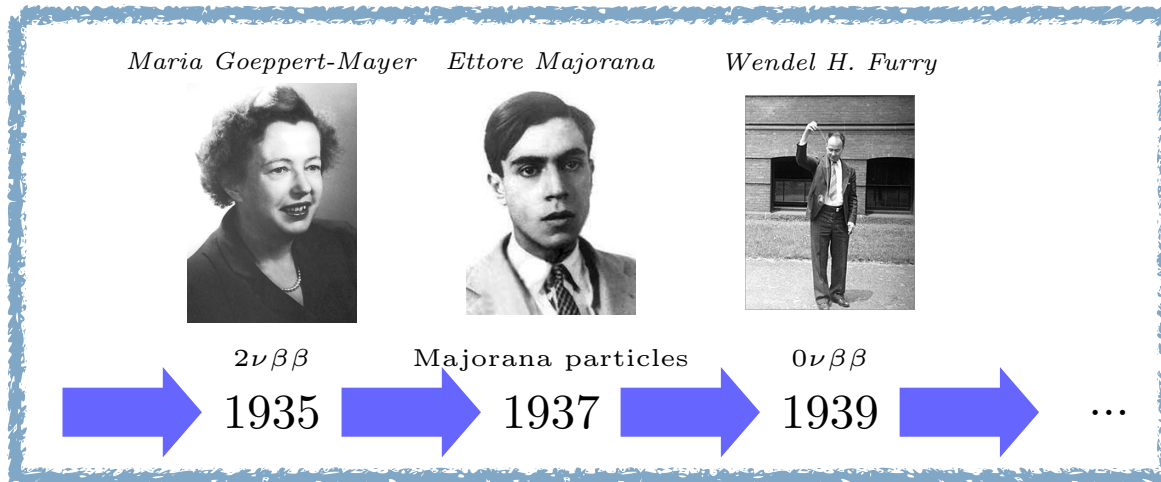
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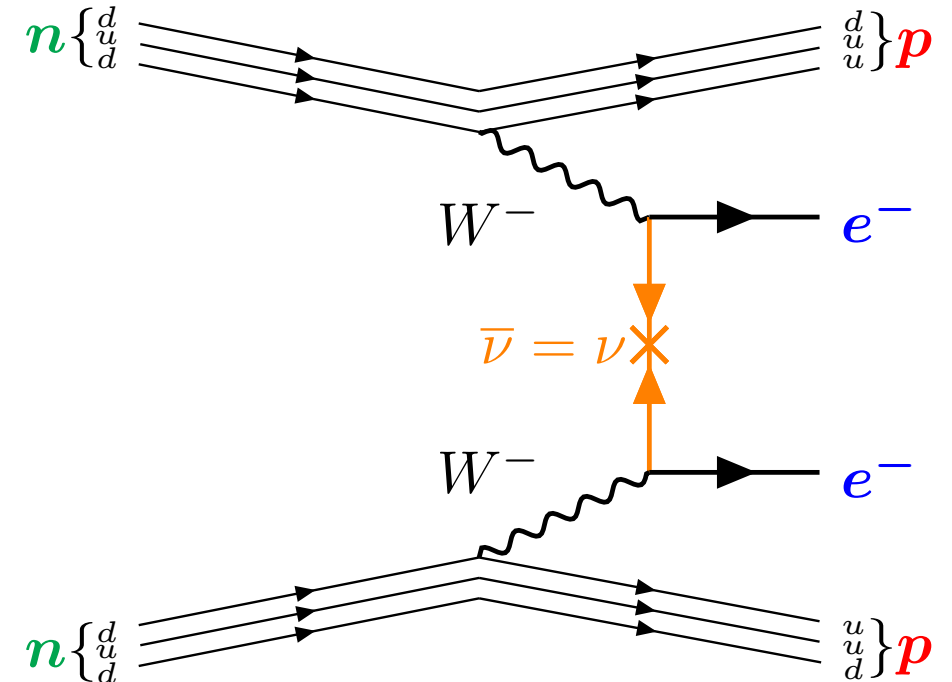
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HALF-LIFE OF $0\nu\beta\beta$ DECAY

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

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

HALF-LIFE OF $0\nu\beta\beta$ DECAY

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

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HALF-LIFE OF $0\nu\beta\beta$ DECAY

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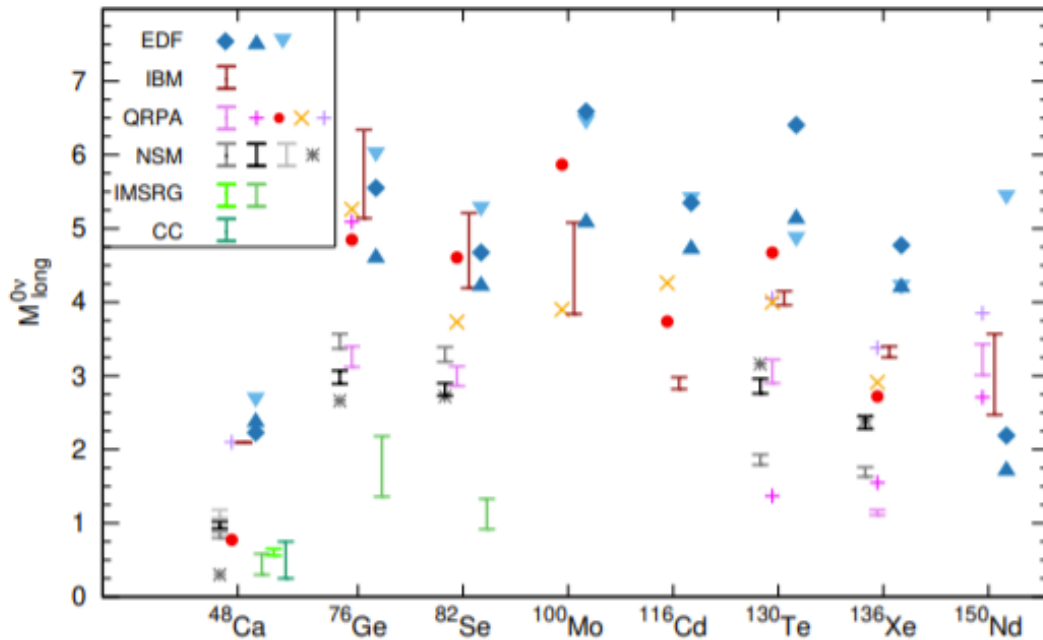
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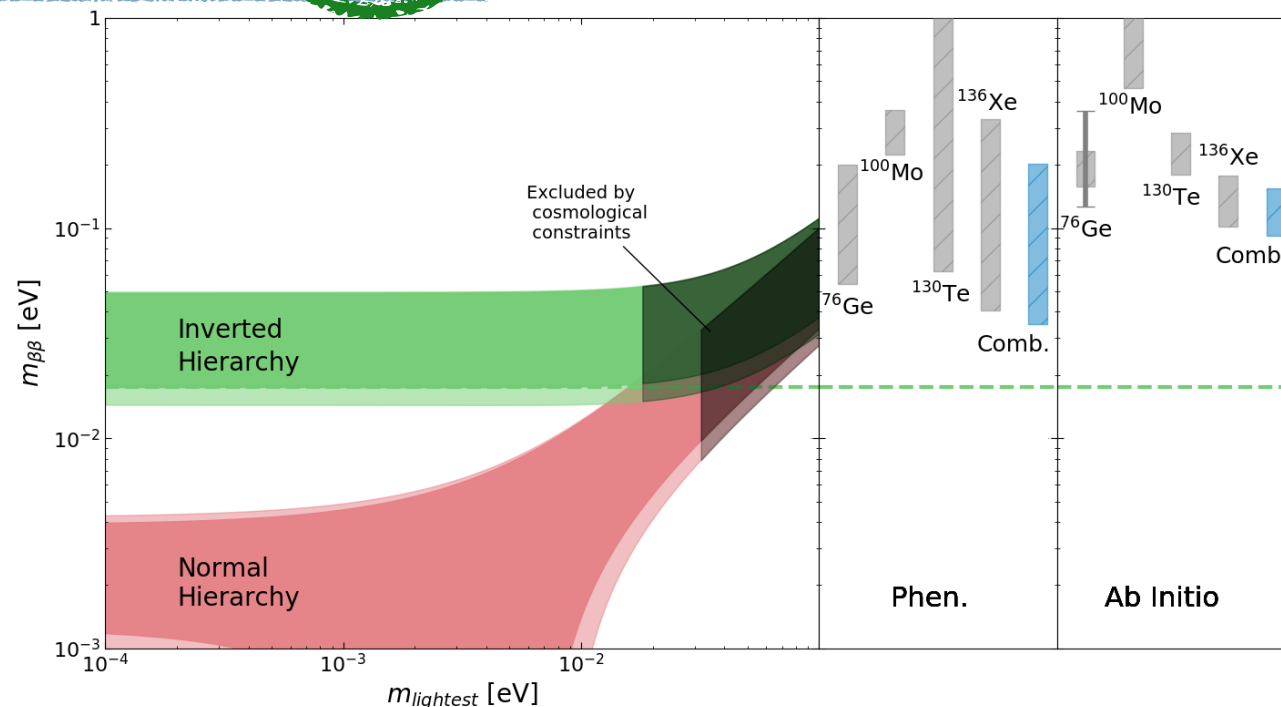
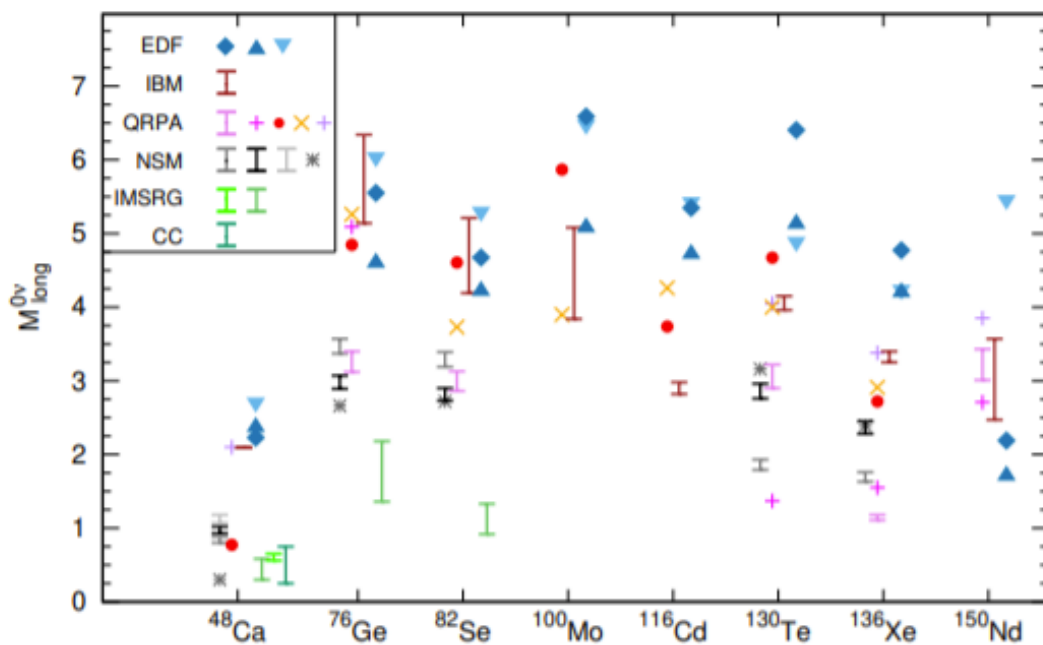
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Shickele, Jokiniemi, Belley, Holt, in preparation

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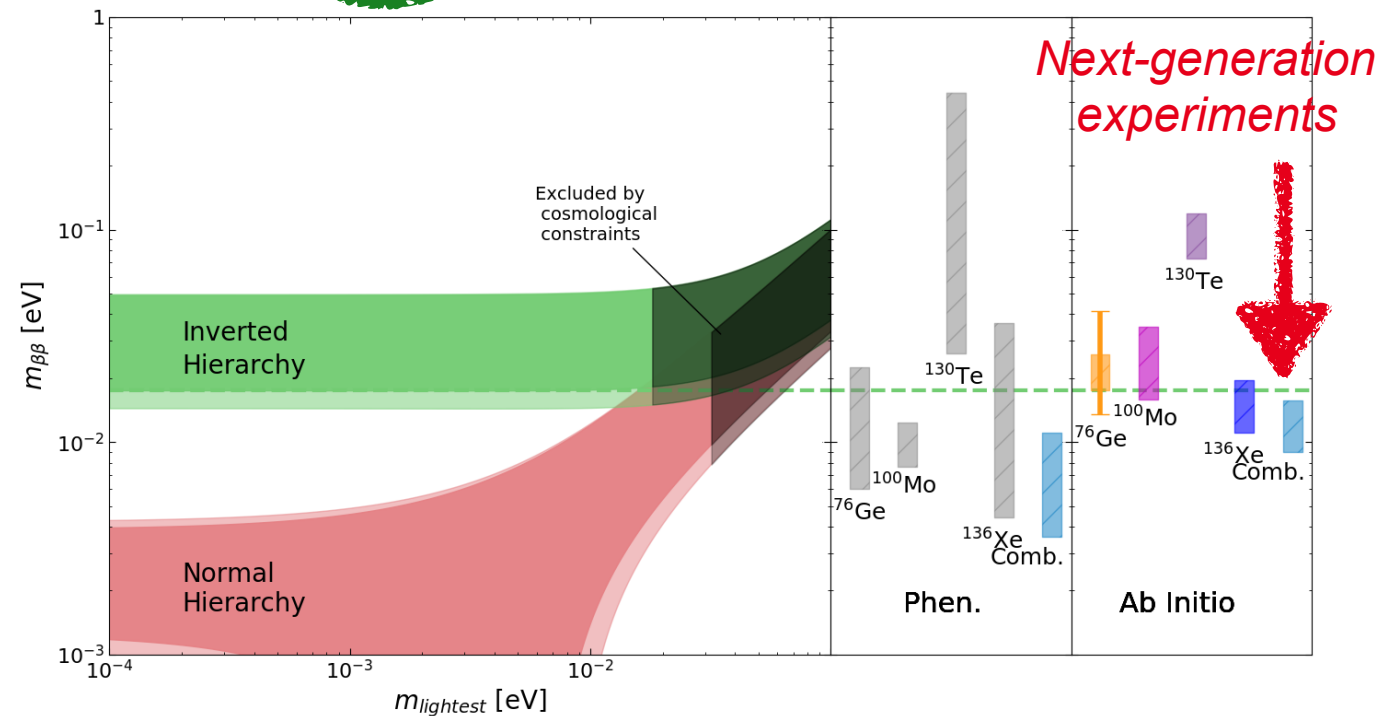
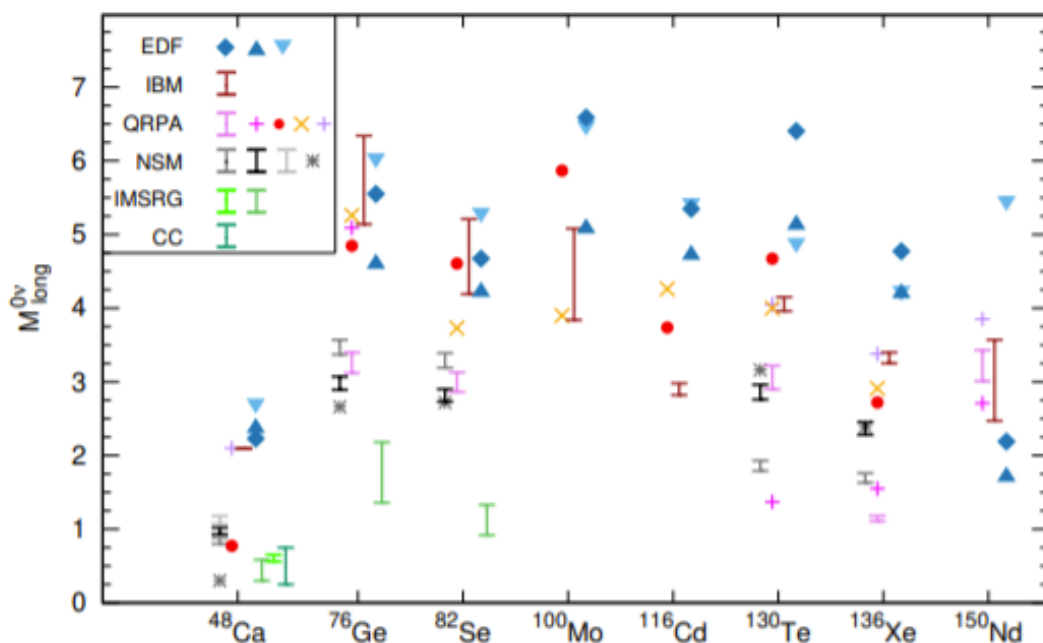
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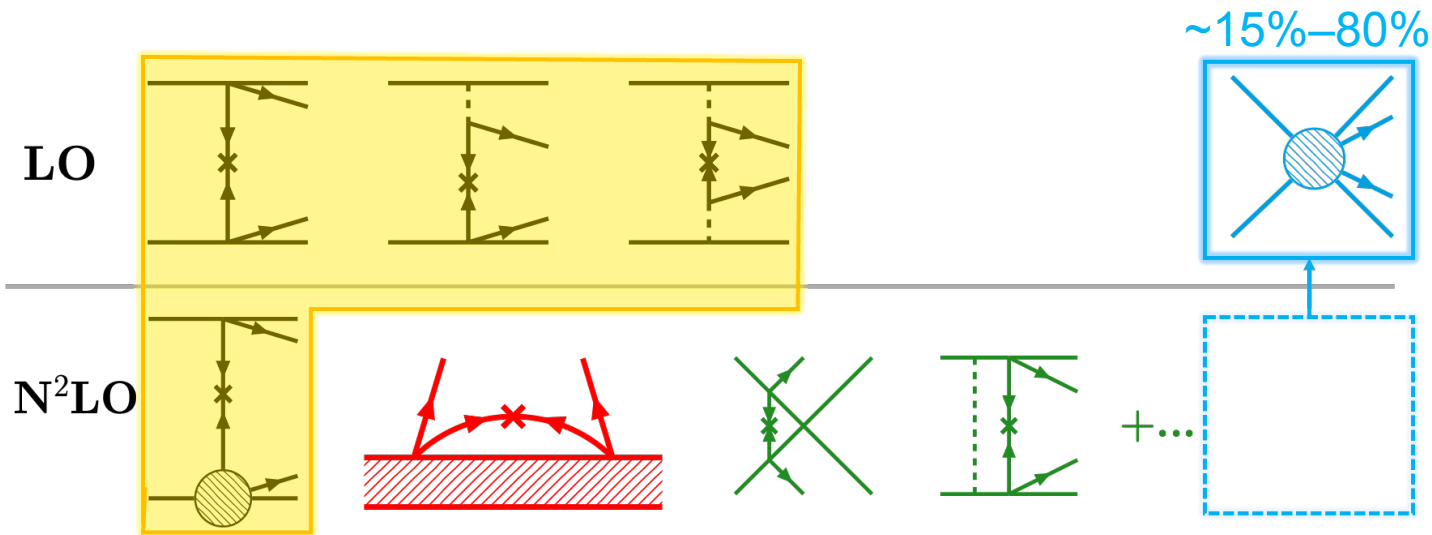
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$$M^{0\nu} = M_{\text{L}}^{0\nu}$$


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

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

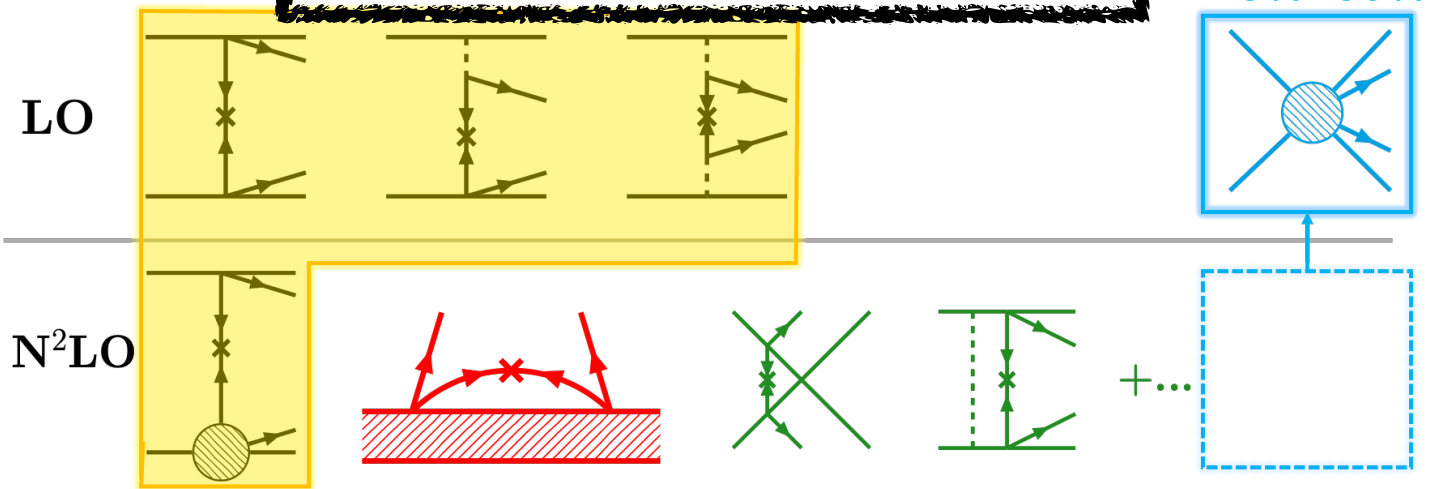


V. Cirigliano et al., *Phys. Rev. Lett.* 120, 202001 (2018), *Phys. Rev. C* 100, 055504 (2019)

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See talk by E. Kauppinen on Tuesday

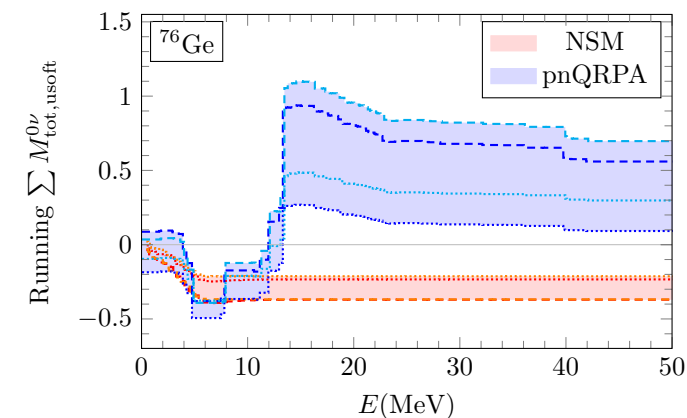
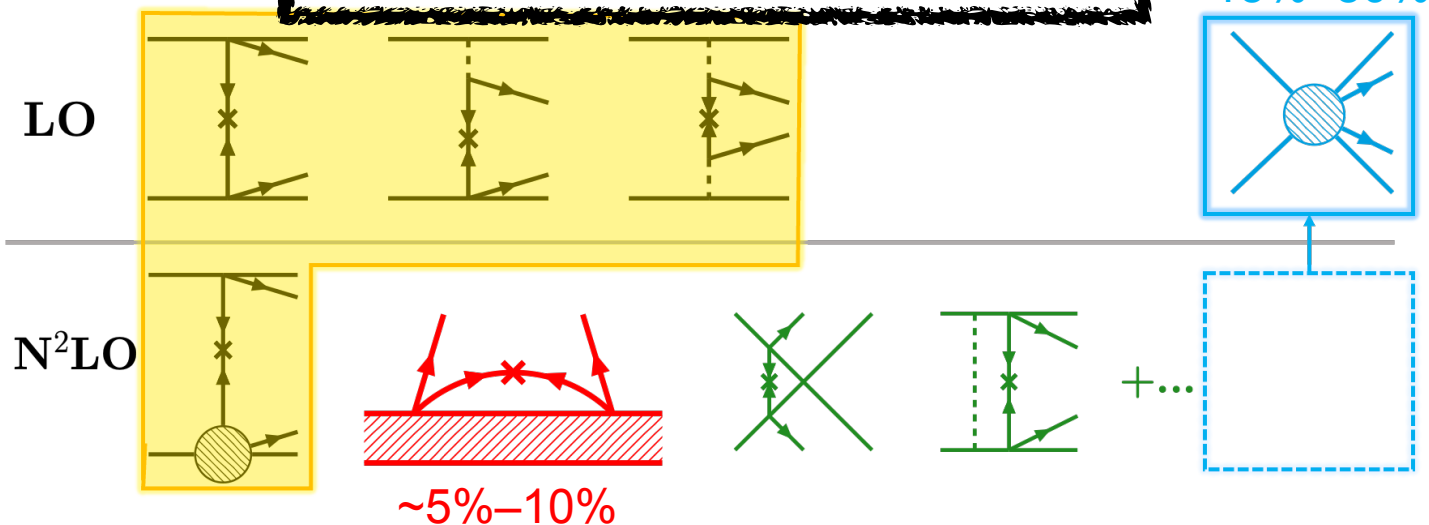


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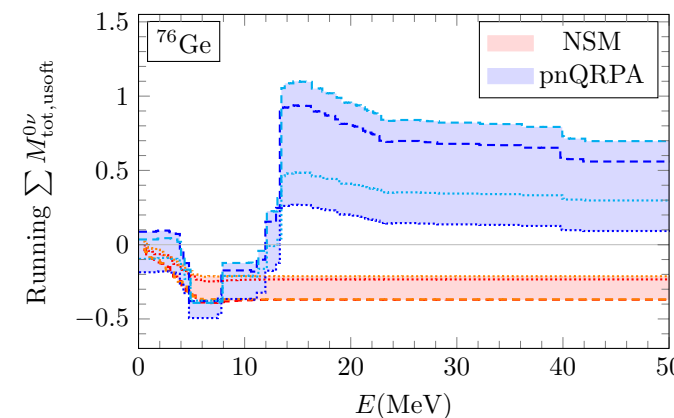
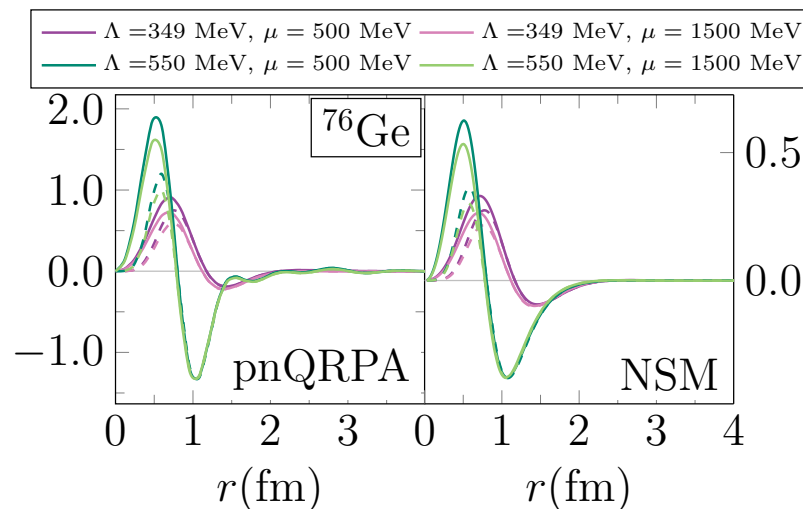
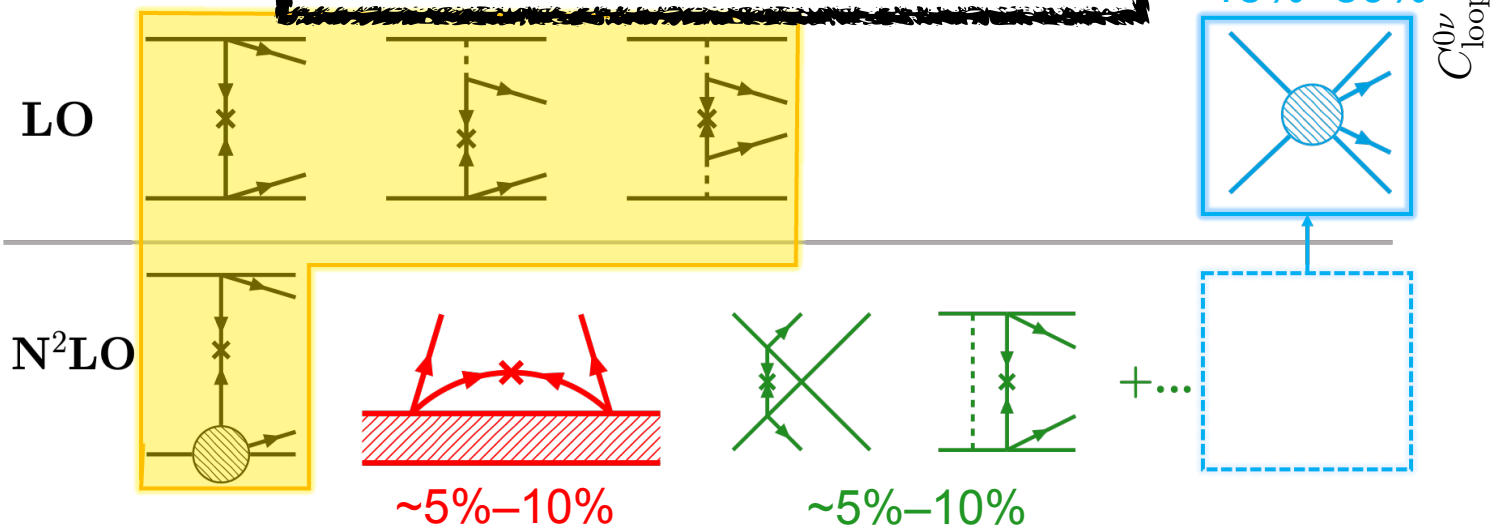
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Castillo, Jokiniemi, Menéndez,
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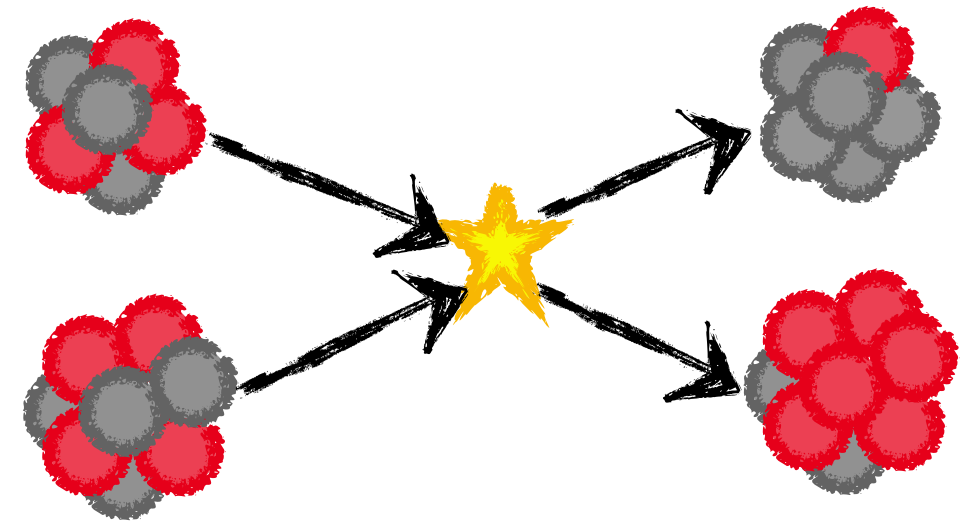


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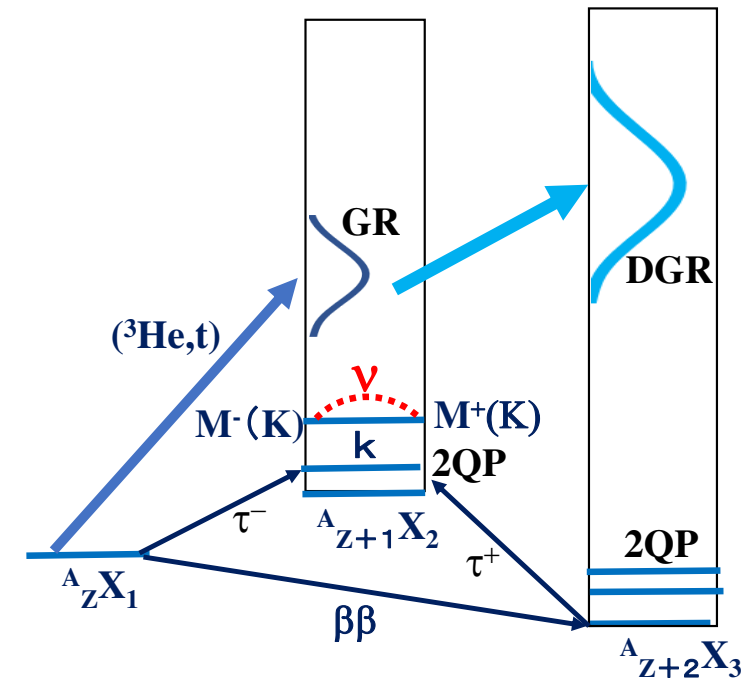
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DOUBLE CHARGE EXCHANGE REACTIONS

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



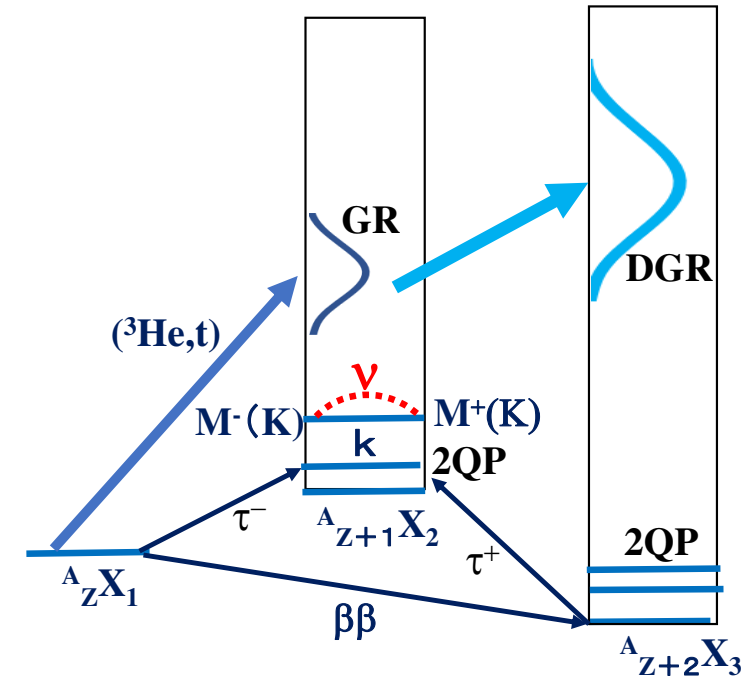
Ejiri, Jokiniemi, Suhonen, Phys. Rev. C 105, L022501 (2022)

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

Leading component

$$M_{GT}^{0\nu} = \langle f || \sum_{jk} \tau_j^- \tau_k^- \sigma_j \sigma_k V_{GT}(r_{jk}) || i \rangle$$



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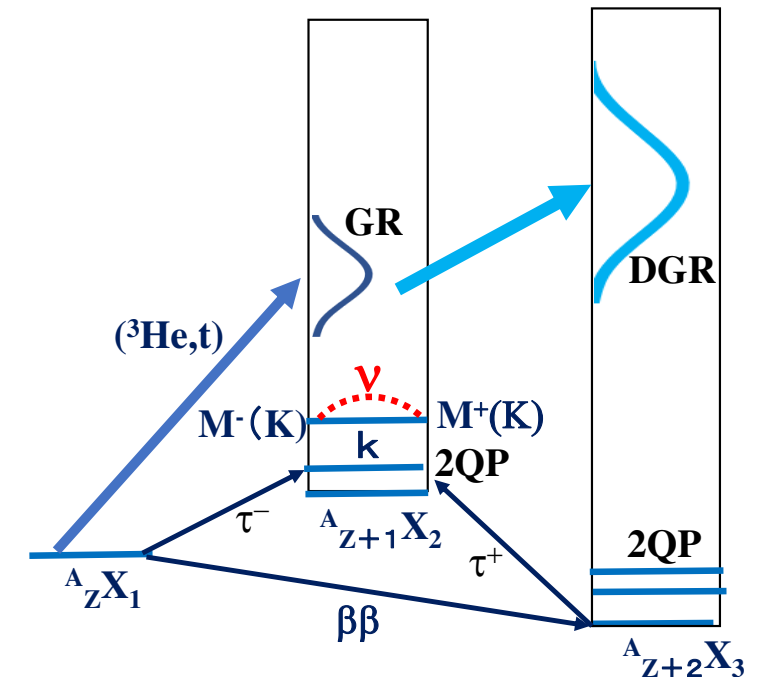
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- Double-Gamow-Teller (DGT) strength function

$$B(\text{DGT}; \lambda) = \frac{1}{2J_i + 1} |\langle j || [\sum_{jk} \sigma_j \tau_j^- \times \sigma_k \tau_k^-]^{(\lambda)} || i \rangle|^2$$



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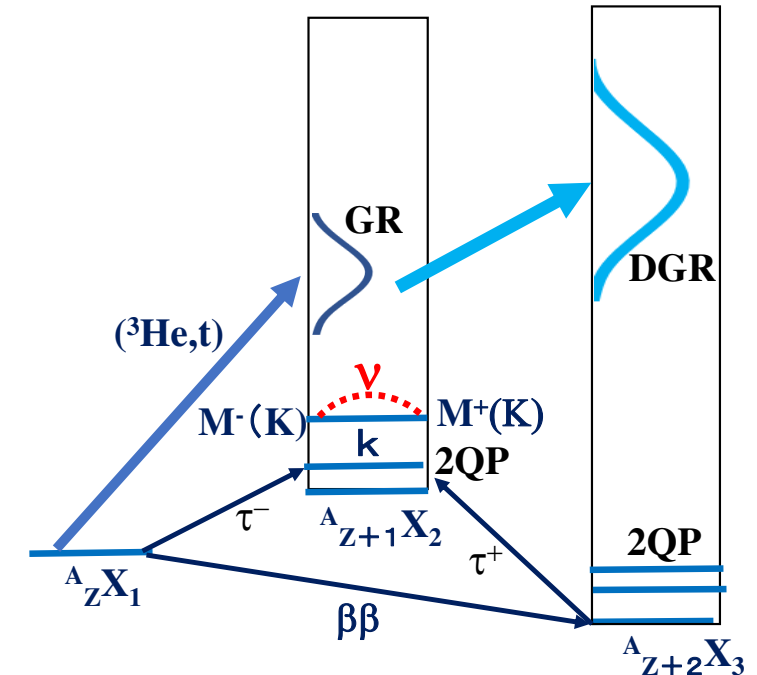
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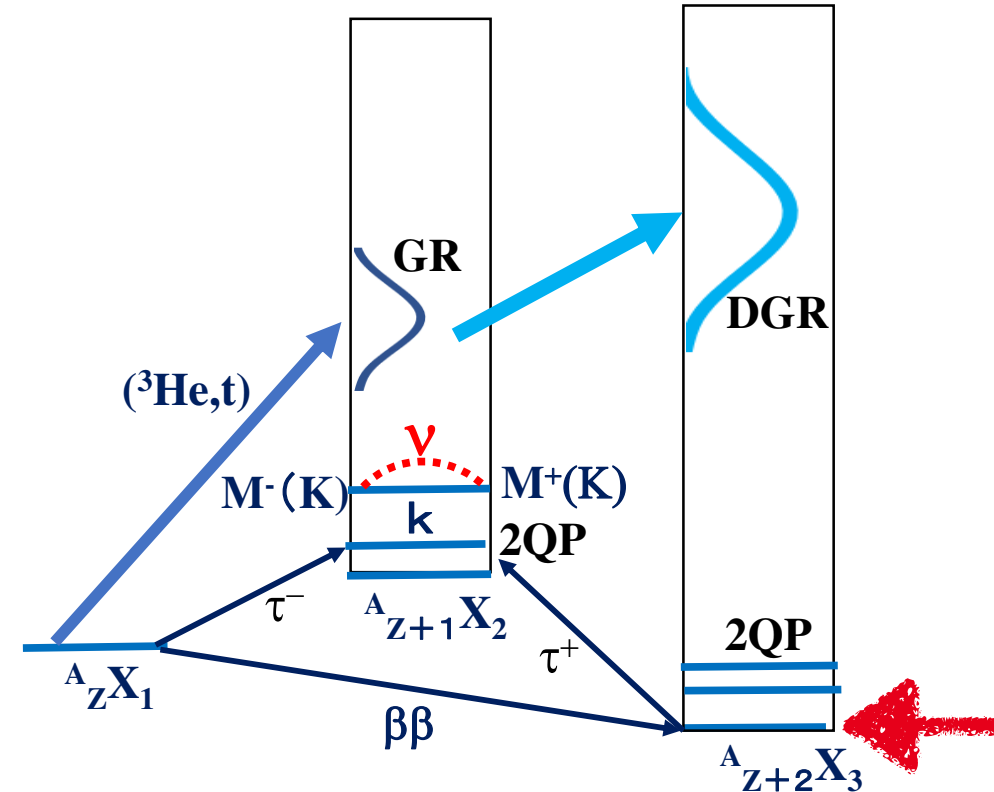
- Very similar operator structures



Ejiri, Jokiniemi, Suhonen, Phys. Rev. C 105, L022501 (2022)

CORRELATIONS BETWEEN DGT AND $0\nu\beta\beta$ DECAY

$$M_{\text{DGT}} = - \langle f | [\sum_{jk} \sigma_j \tau_j^- \times \sigma_k \tau_k^-]^{(0)} | i \rangle$$

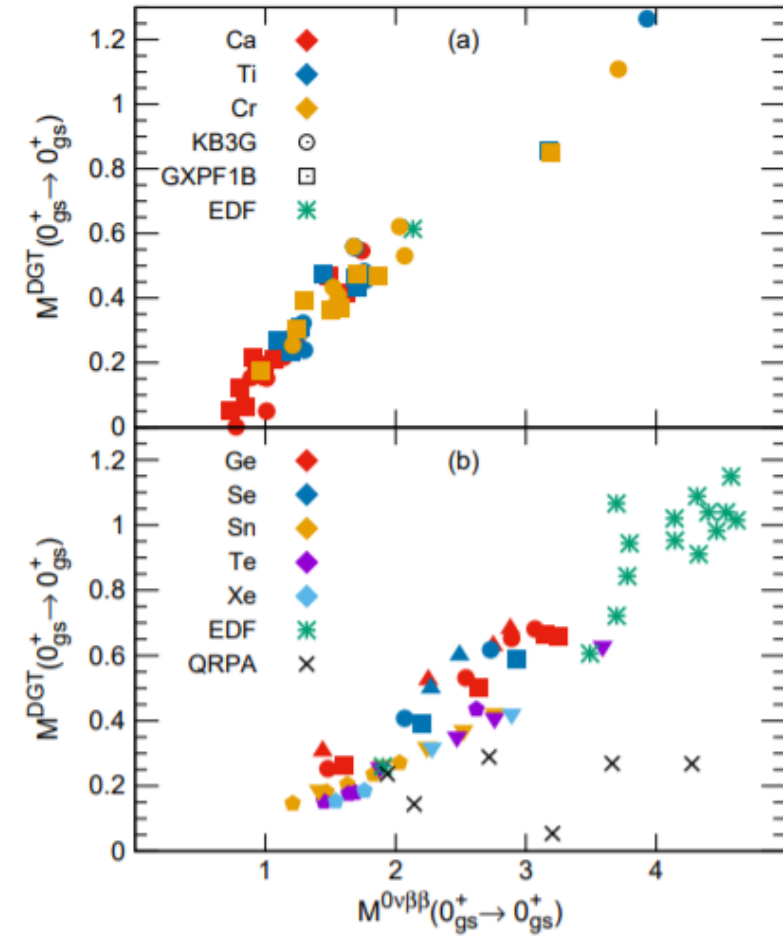


Ejiri, Jokiniemi, Suhonen, Phys. Rev. C 105, L022501 (2022)

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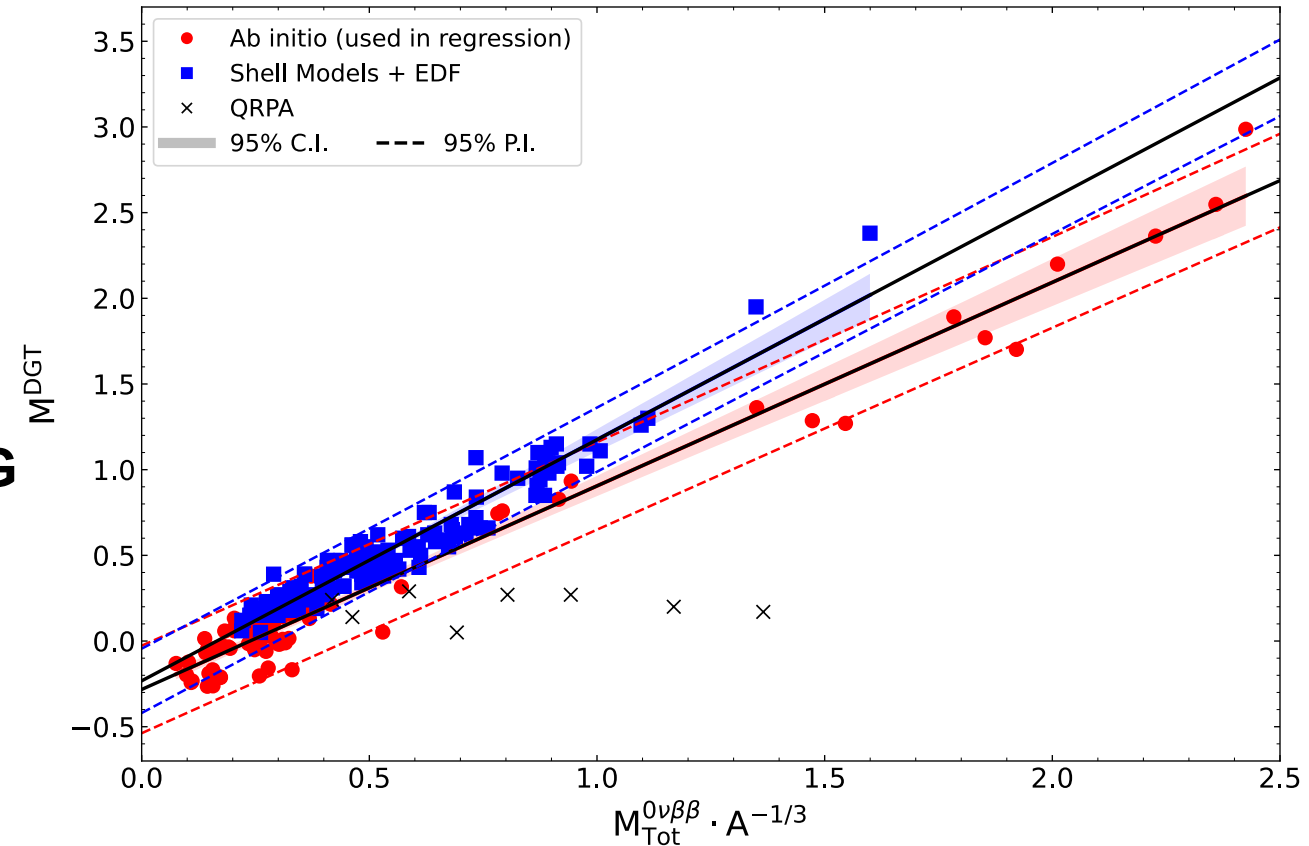


Shimizu, Menéndez, Yako, *Phys. Rev. Lett.* 120, 142502 (2018)

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- Correlation also holds in ***ab initio* VS-IMSRG**

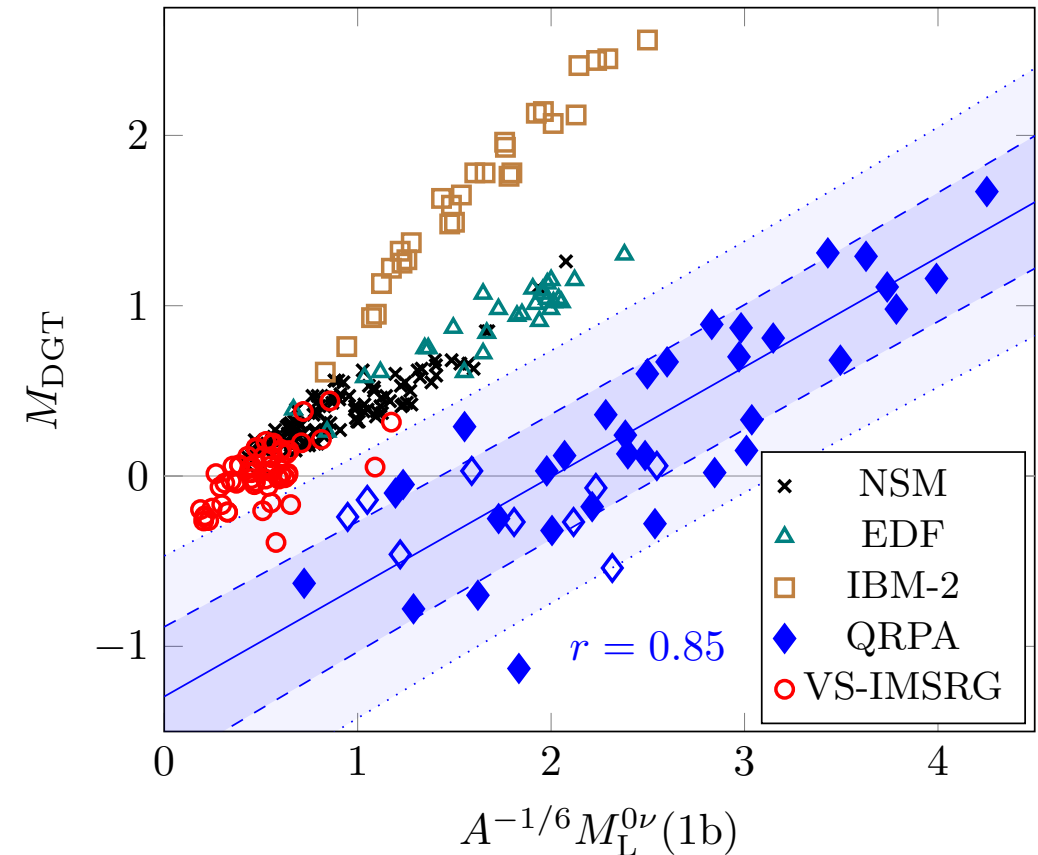


Yao, Ginnett, Belley et al., Phys. Rev. C 106, 014315 (2022)

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- ... and **QRPA**, when proton-neutron pairing is varied



Jokiniemi, Menéndez, *Phys. Rev. C* 107, 044316 (2024)

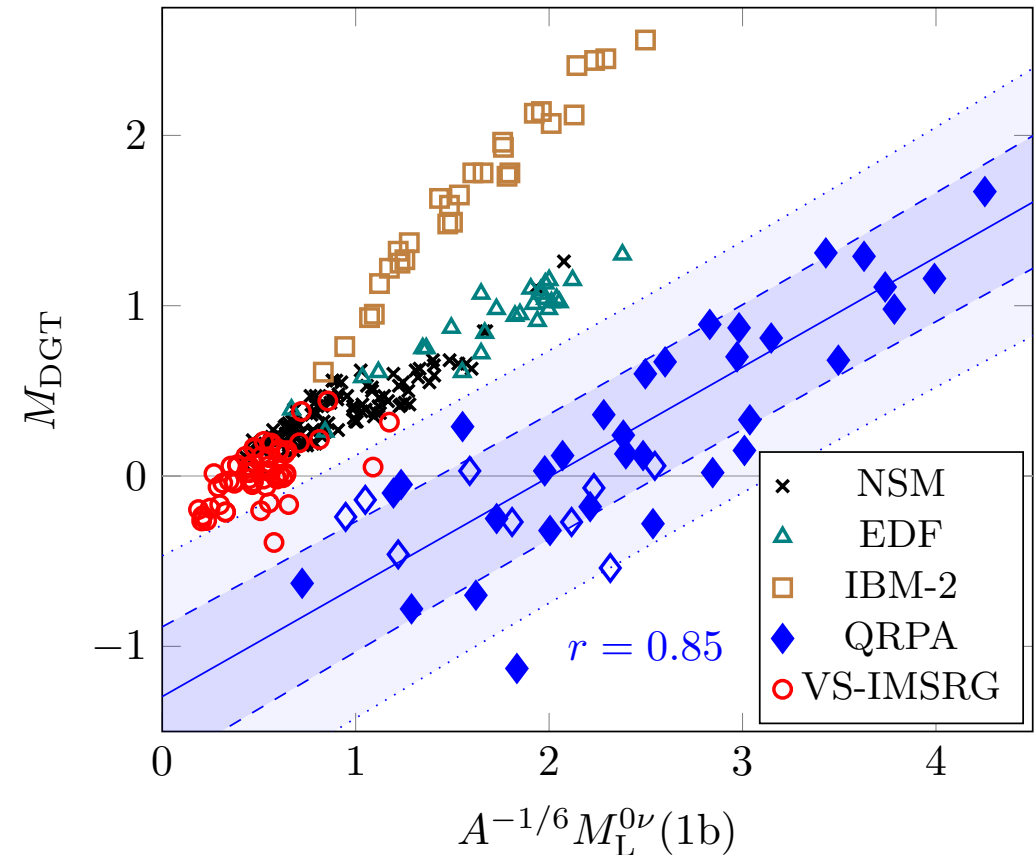
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Observation of DGT strength would help constrain $M^{0\nu}$



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CORRELATIONS BETWEEN DGT AND $0\nu\beta\beta$ DECAY

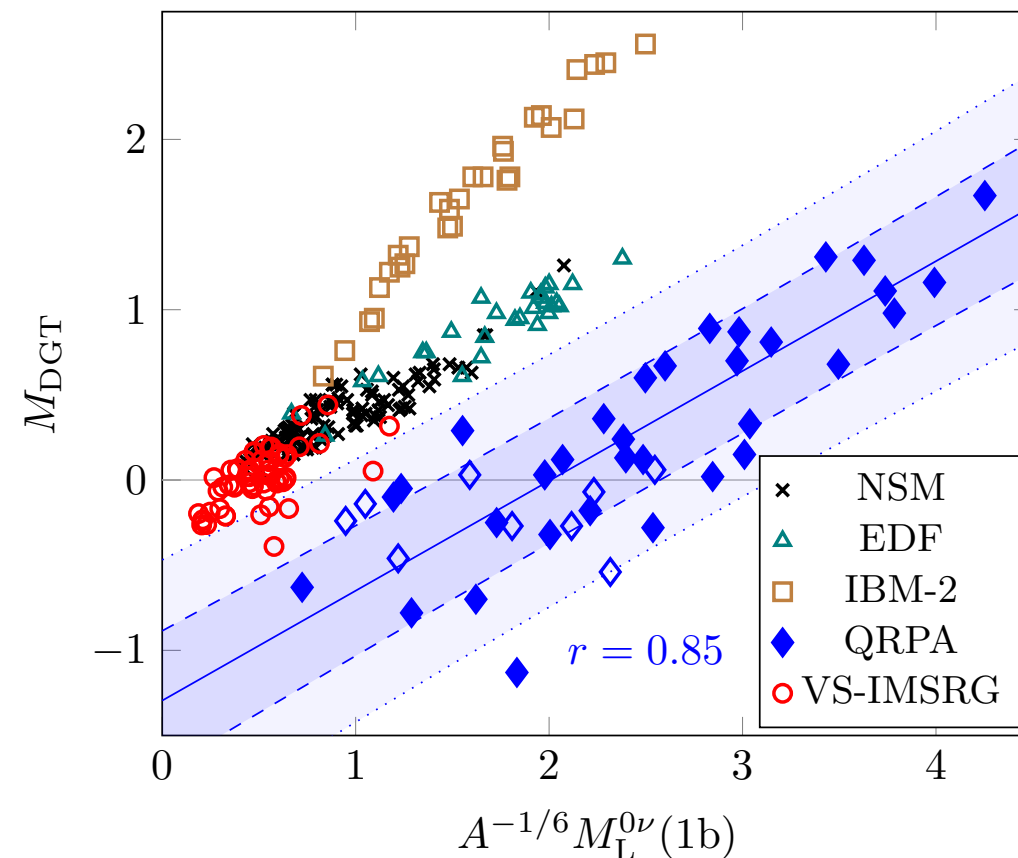
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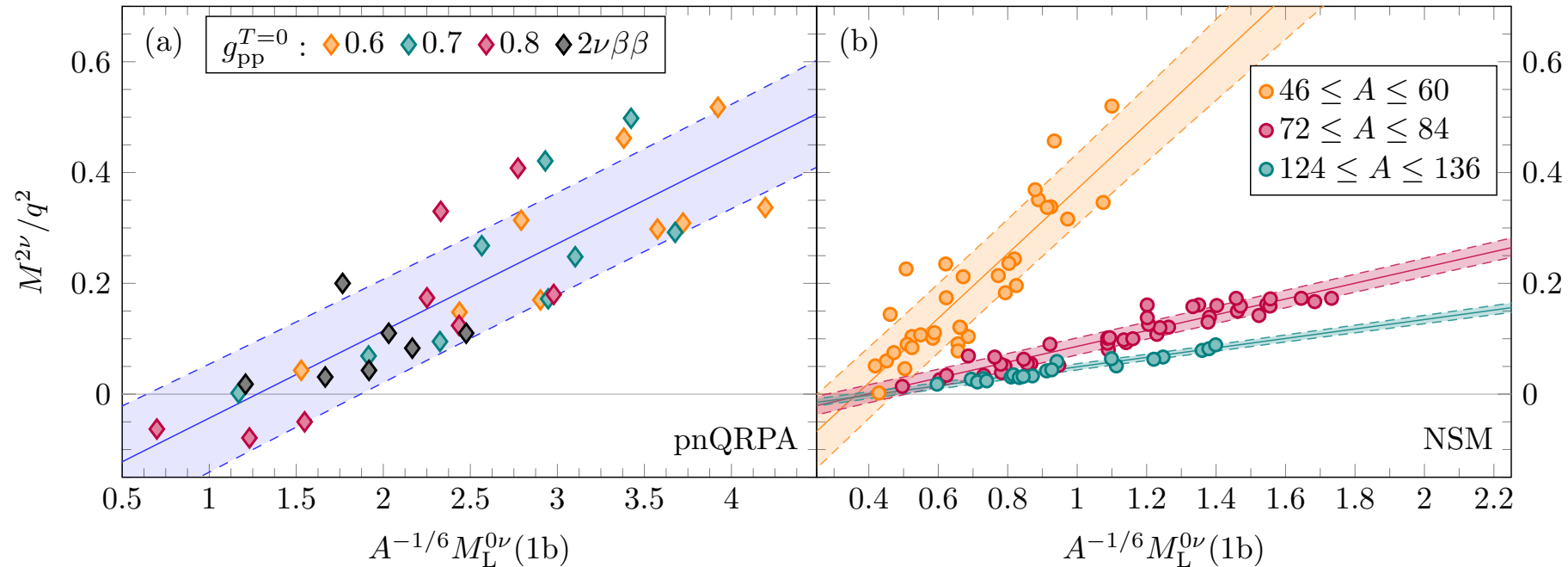
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PROBING $0\nu\beta\beta$ DECAY BY $2\nu\beta\beta$ DECAY

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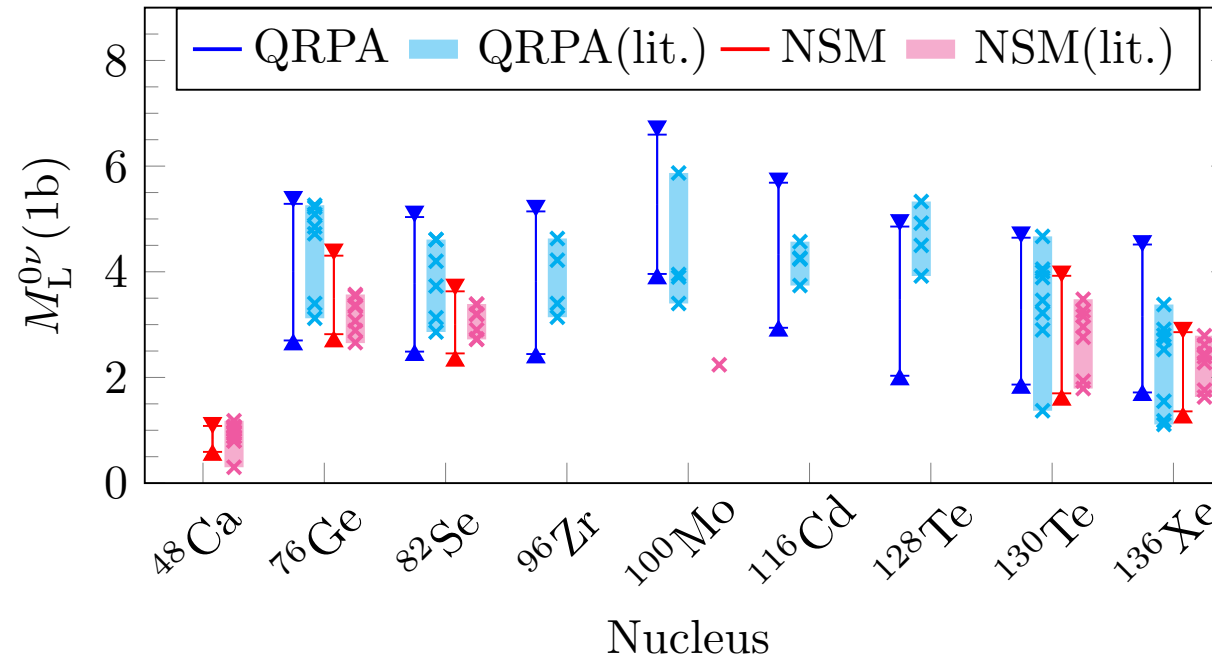
- $2\nu\beta\beta$ decay also correlated with $0\nu\beta\beta$ decay



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

PROBING $0\nu\beta\beta$ DECAY BY $2\nu\beta\beta$ DECAY

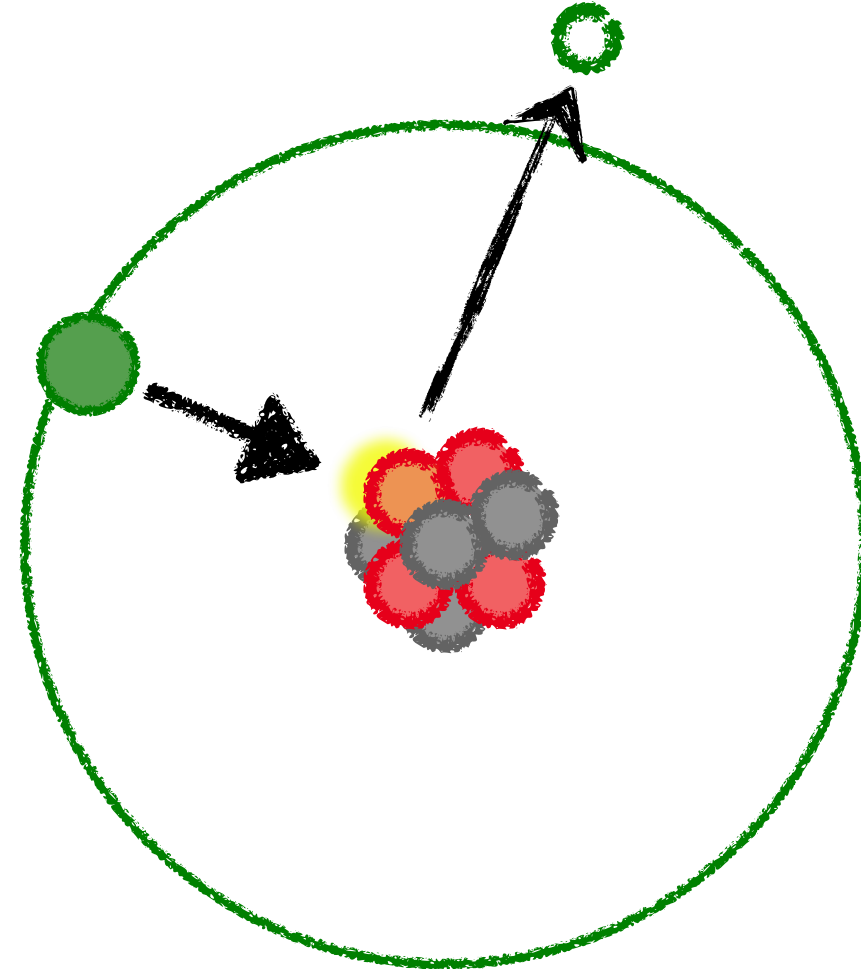
- $2\nu\beta\beta$ decay also correlated with $0\nu\beta\beta$ decay
- We can use existing data to estimate $0\nu\beta\beta$ -decay NMEs with uncertainties



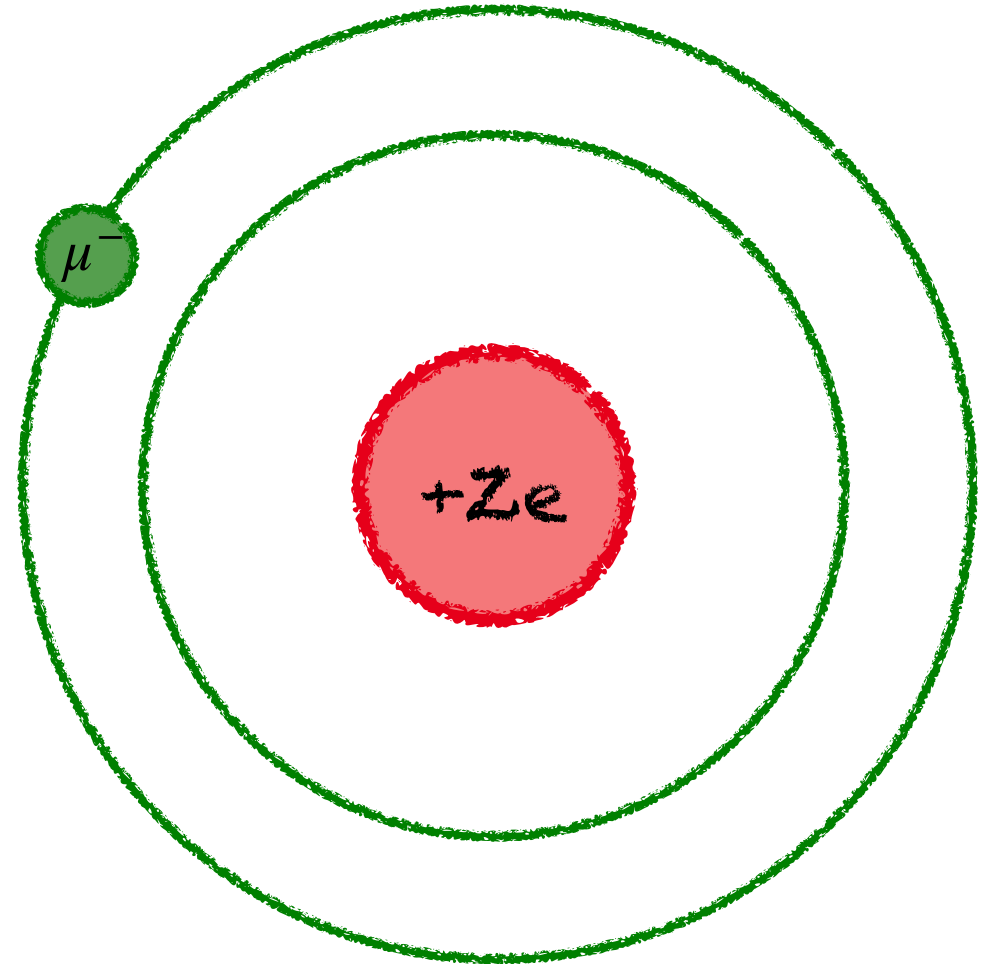
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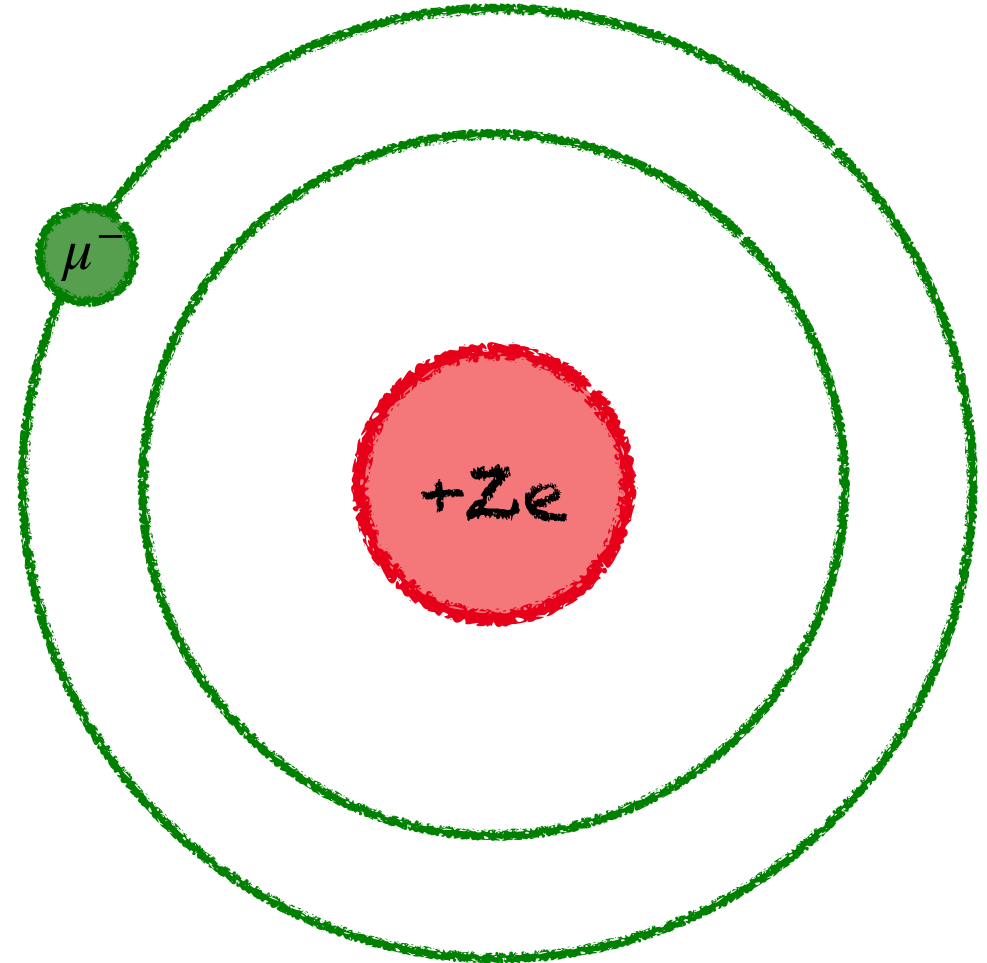


ORDINARY MUON CAPTURE



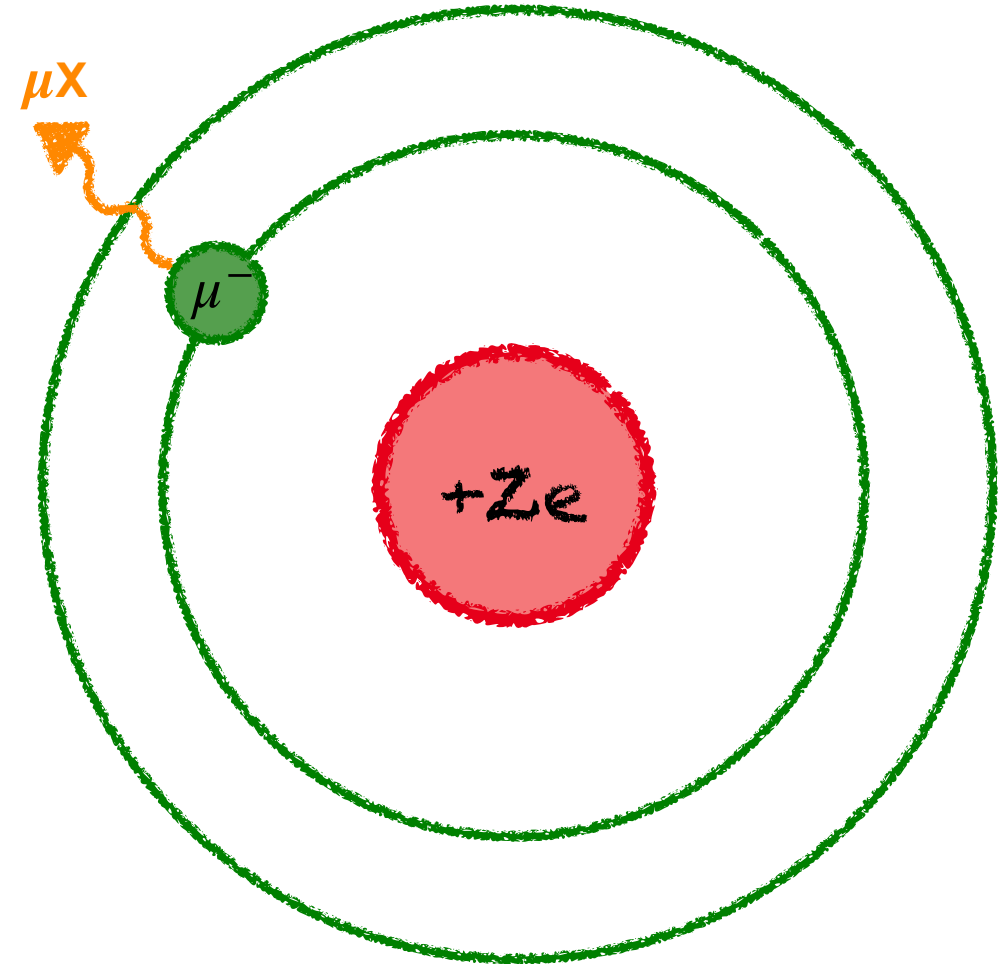
ORDINARY MUON CAPTURE

- Starting point: **a muonic atom**



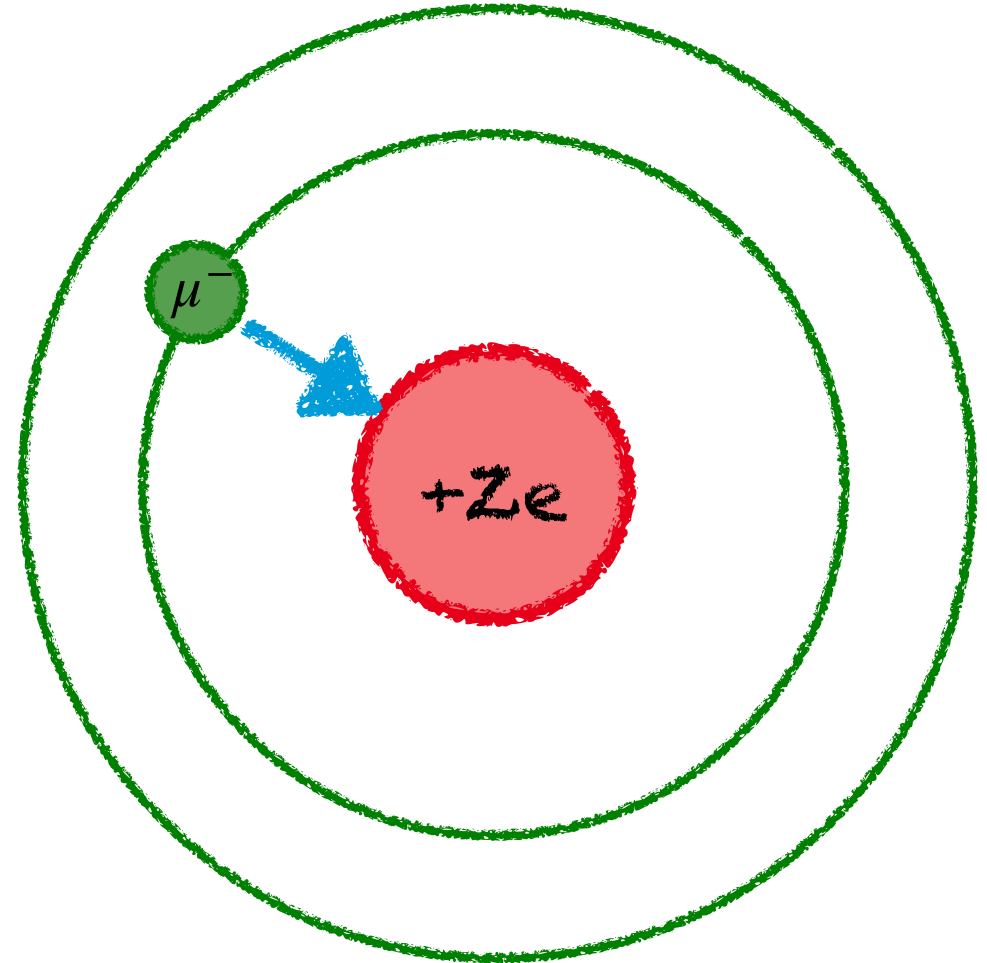
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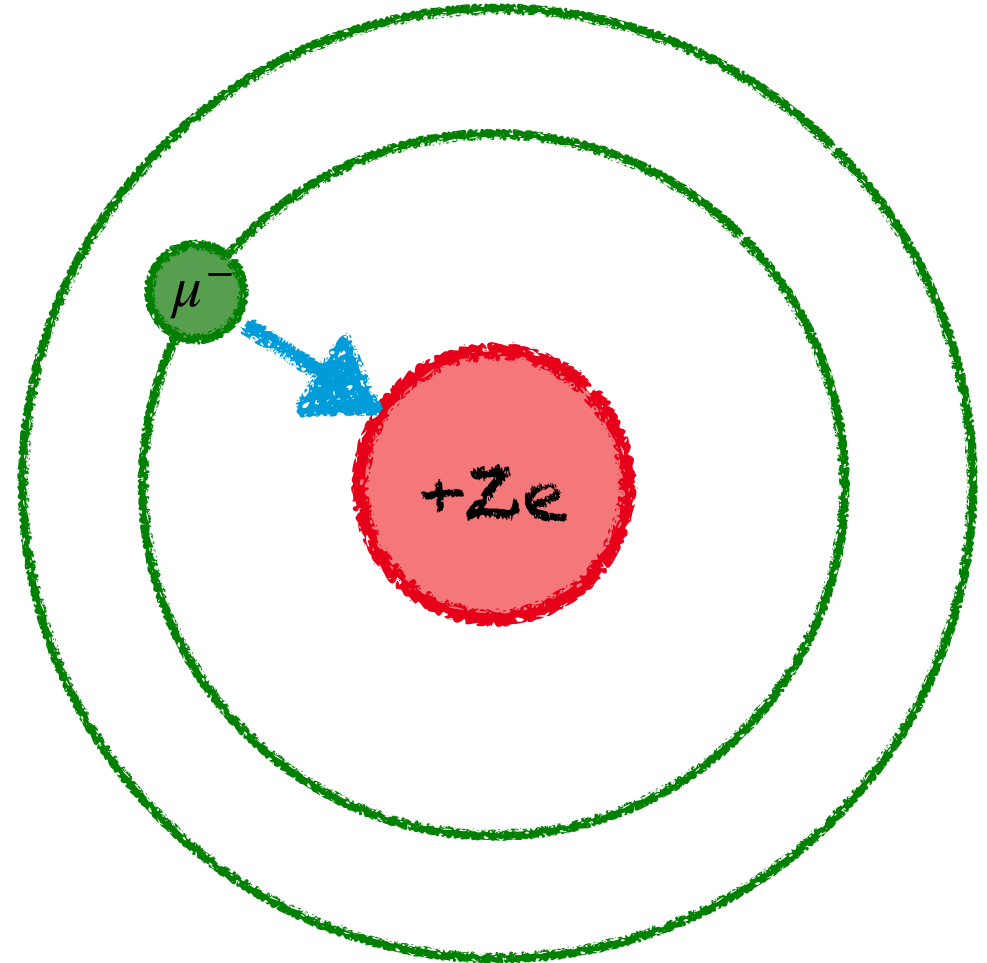
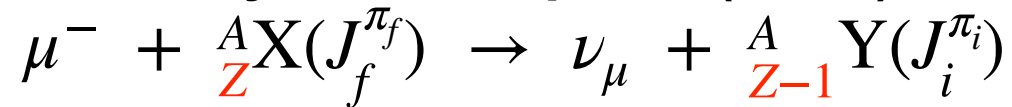
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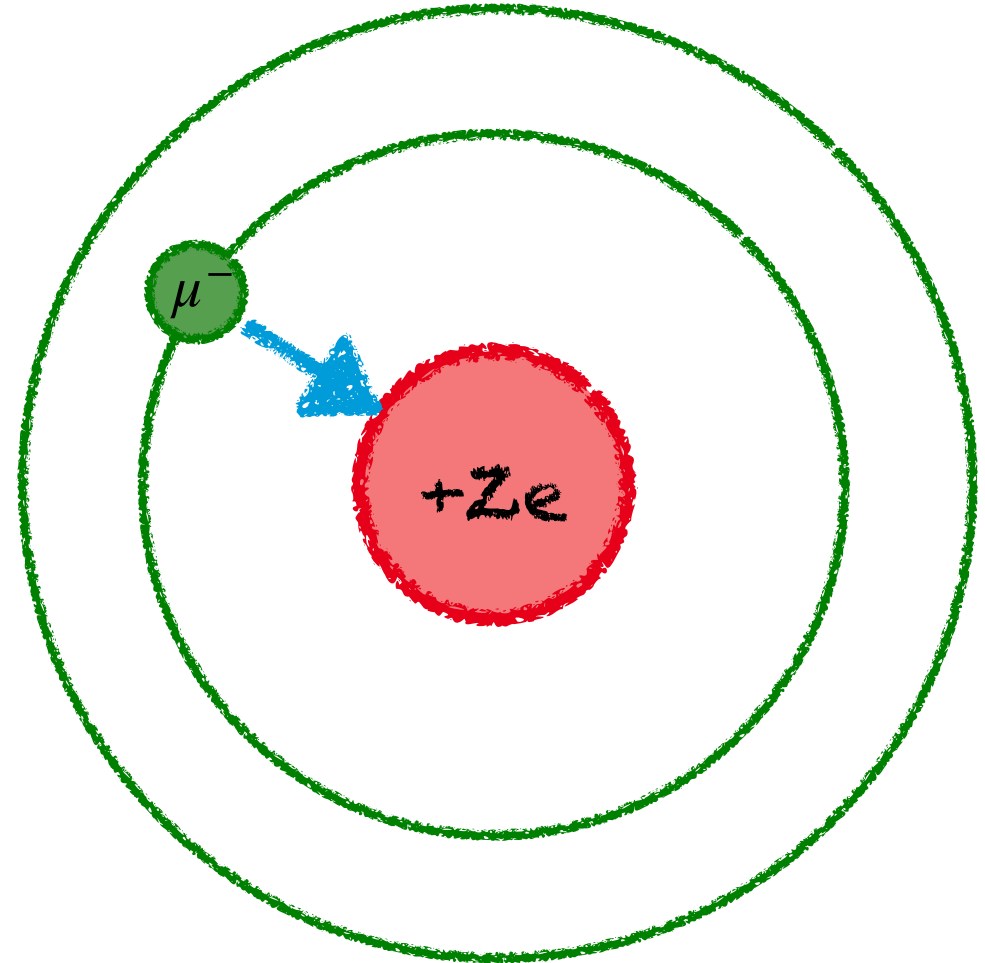


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 - Ordinary muon capture (OMC):**

$$\mu^- + {}^A_Z\text{X}(J_f^{\pi_f}) \rightarrow \nu_\mu + {}^A_{Z-1}\text{Y}(J_i^{\pi_i})$$
 - Radiative muon capture (RMC):**

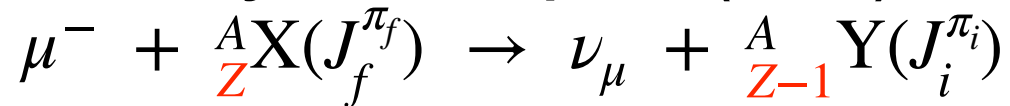
$$\mu^- + {}^A_Z\text{X}(J_f^{\pi_f}) \rightarrow \nu_\mu + {}^A_{Z-1}\text{Y}(J_i^{\pi_i}) + \gamma$$



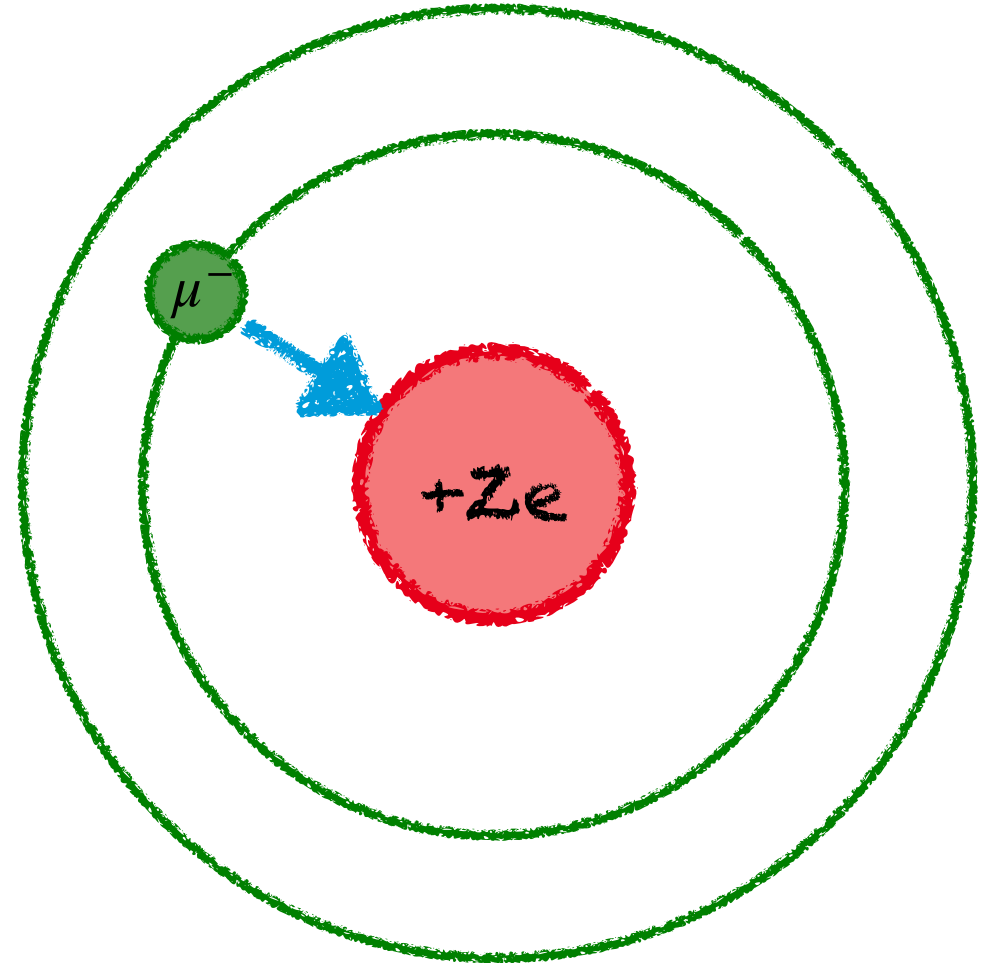
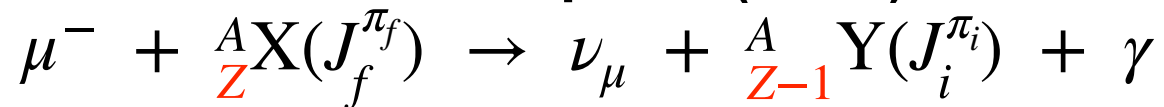
ORDINARY MUON CAPTURE

- Starting point: **a muonic atom**
- The muon quickly transitions to the lowest, **$1s_{1/2}$ orbit**
- From there, the muon can be **captured by the nucleus**

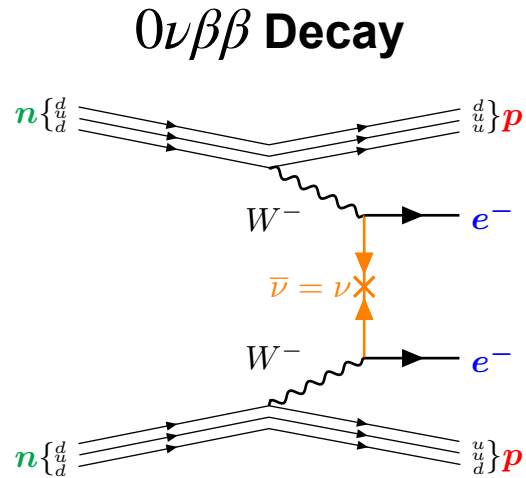
- Ordinary muon capture (OMC):**



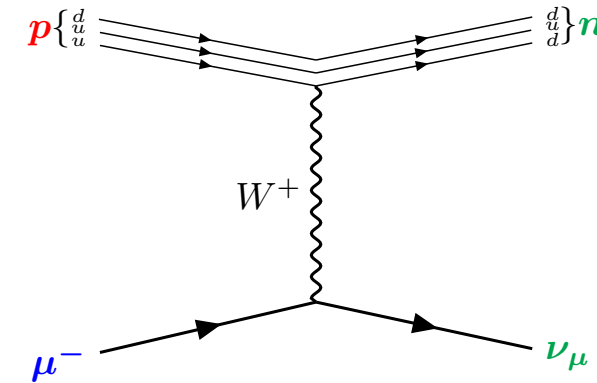
- Radiative muon capture (RMC):**



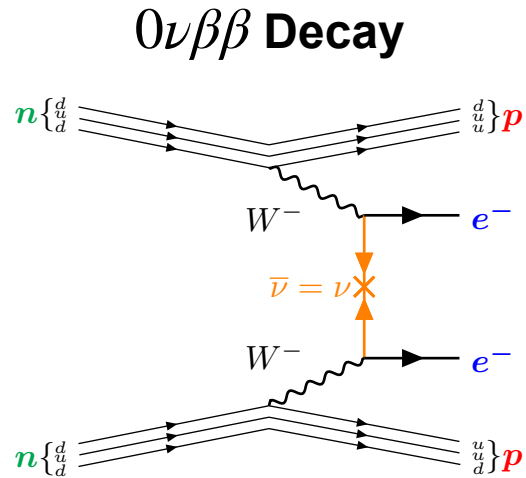
$0\nu\beta\beta$ DECAY VS. ORDINARY MUON CAPTURE



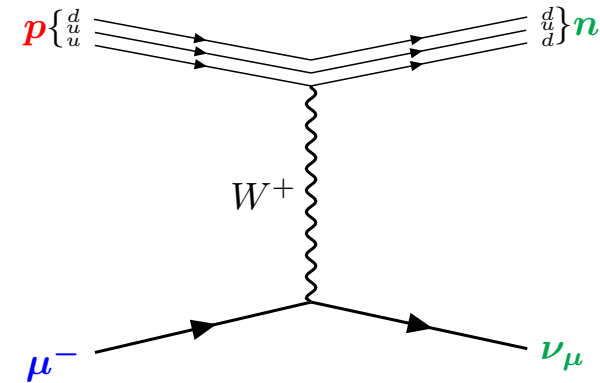
Ordinary Muon Capture



$0\nu\beta\beta$ DECAY VS. ORDINARY MUON CAPTURE

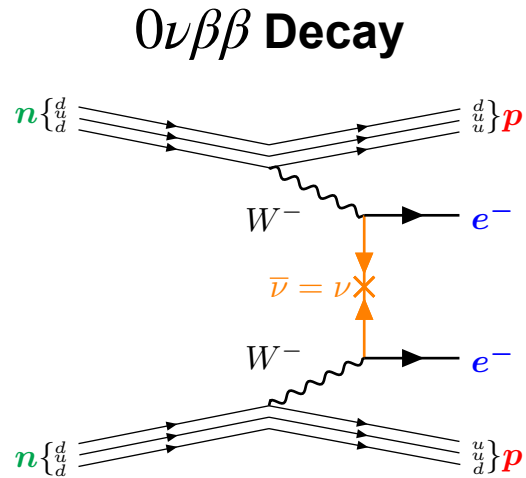


Ordinary Muon Capture



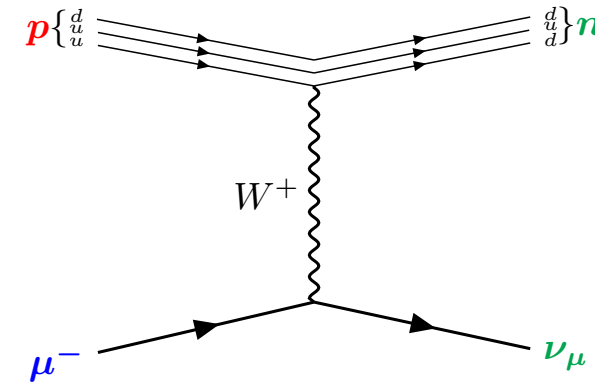
- $q \approx 1/|\mathbf{r}_1 - \mathbf{r}_2| \approx 100 - 200 \text{ MeV}$

$0\nu\beta\beta$ DECAY VS. ORDINARY MUON CAPTURE



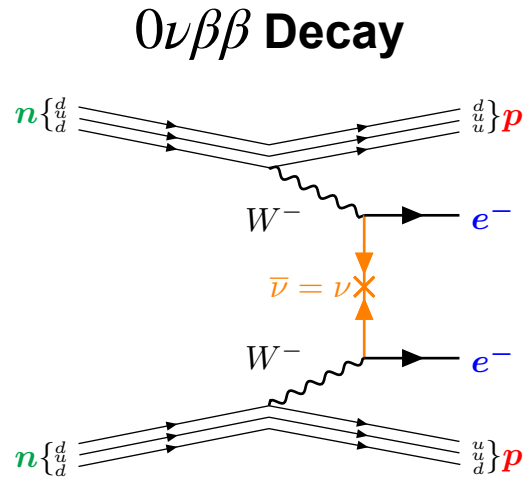
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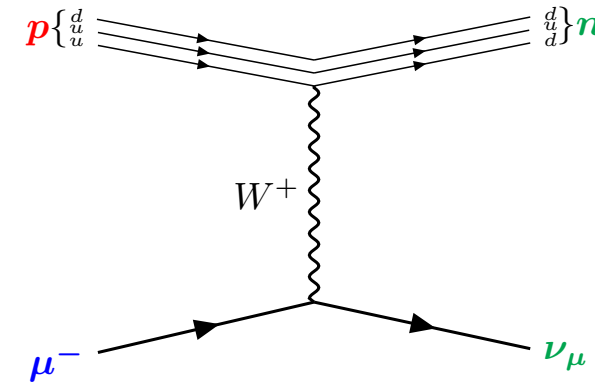
- $q \approx m_\mu + E_i - E_f \approx 100 \text{ MeV}$

$0\nu\beta\beta$ DECAY VS. ORDINARY MUON CAPTURE



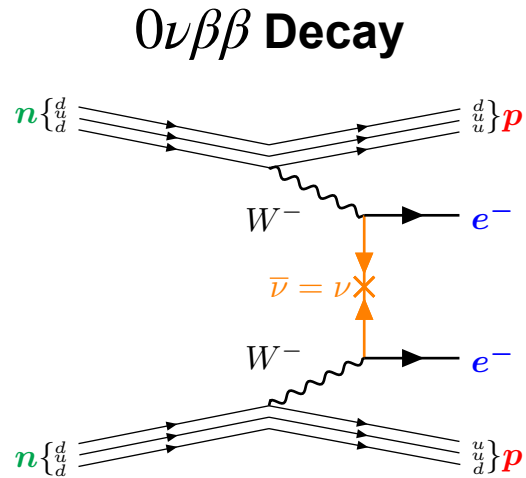
- $q \approx 1/|\mathbf{r}_1 - \mathbf{r}_2| \approx 100 - 200 \text{ MeV}$
- No experimental signal so far

Ordinary Muon Capture



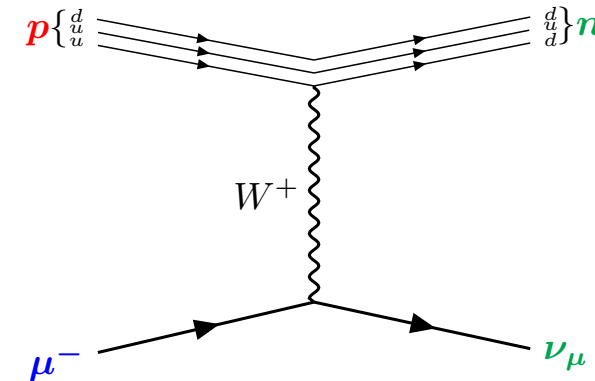
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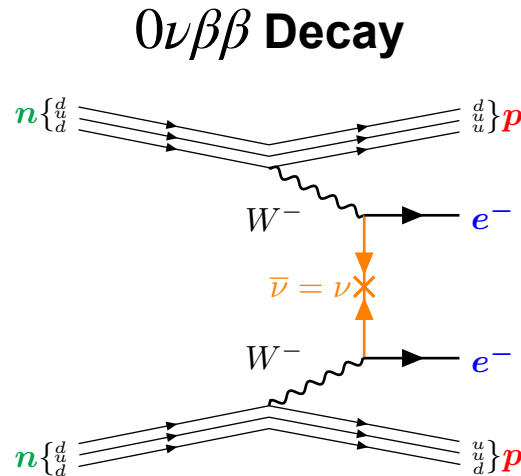
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- **No experimental signal so far**

Ordinary Muon Capture

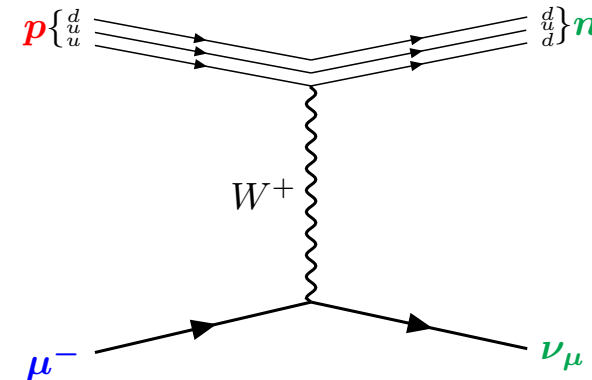


- $q \approx m_\mu + E_i - E_f \approx 100 \text{ MeV}$
- **Has been measured**

$0\nu\beta\beta$ DECAY VS. ORDINARY MUON CAPTURE



Ordinary Muon Capture



- $q \approx 1/|\mathbf{r}_1 - \mathbf{r}_2| \approx 100 - 200 \text{ MeV}$
- **No experimental signal so far**

- $q \approx m_\mu + E_i - E_f \approx 100 \text{ MeV}$
- **Has been measured**

$$j^{\alpha\dagger} = \bar{\Psi} [g_V(\mathbf{q}^2)\gamma^\alpha + ig_M(\mathbf{q}^2)\frac{\sigma^{\alpha\beta}}{2M}q_\beta - g_A(\mathbf{q}^2)\gamma^\alpha\gamma_5 - g_P(\mathbf{q}^2)q^\alpha\gamma_5] \Psi$$



MONUMENT (OMC4DBD) EXPERIMENT @ PSI

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

THE EUROPEAN
PHYSICAL JOURNAL C



Regular Article

Experimental Physics

The MONUMENT experiment: ordinary muon capture studies for $0\nu\beta\beta$ decay

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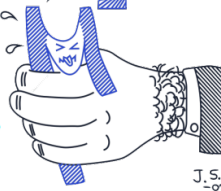
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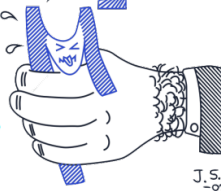
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- Aim 1: Measure OMC in $\beta\beta$ -decay nuclei





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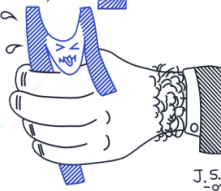


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- **Aim 1:** Measure OMC in $\beta\beta$ -decay nuclei
- **Aim 2:** Measure OMC in light nuclei accessible by *ab initio* nuclear theory





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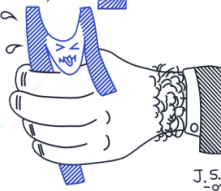


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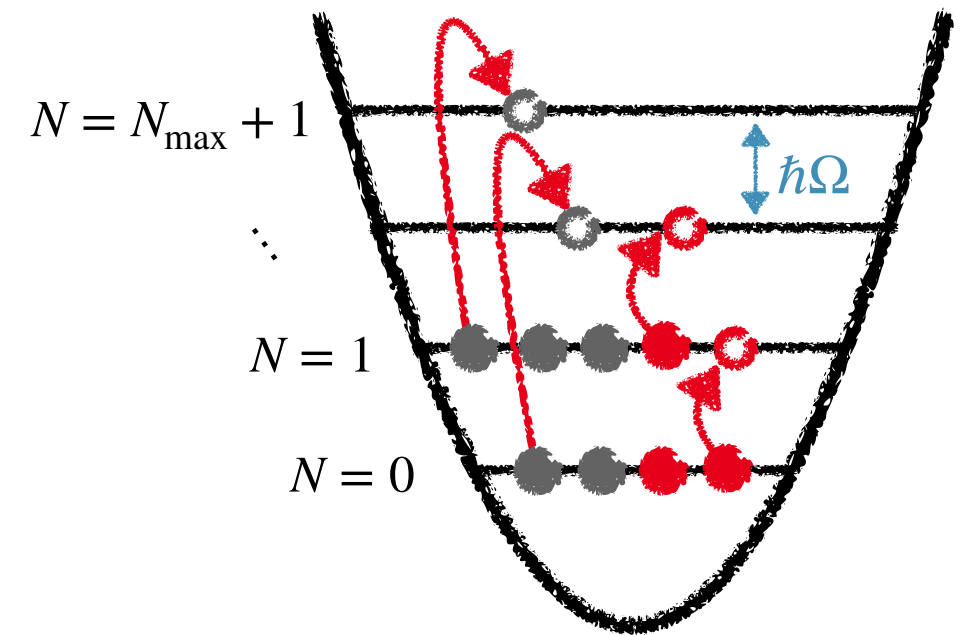
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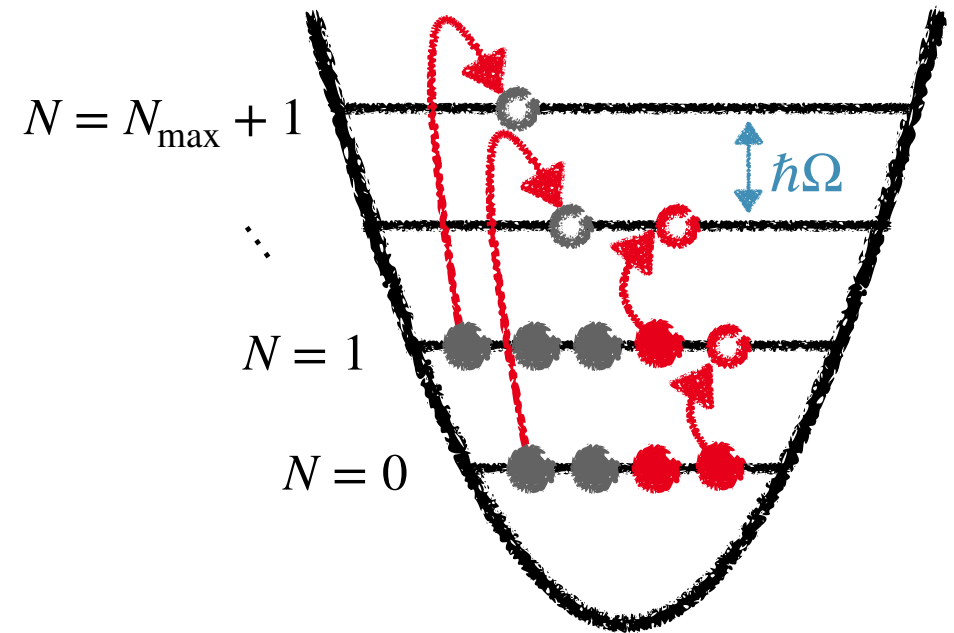
NO-CORE SHELL MODEL (NCSM)



NO-CORE SHELL MODEL (NCSM)

- Solve the nuclear many-body problem

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



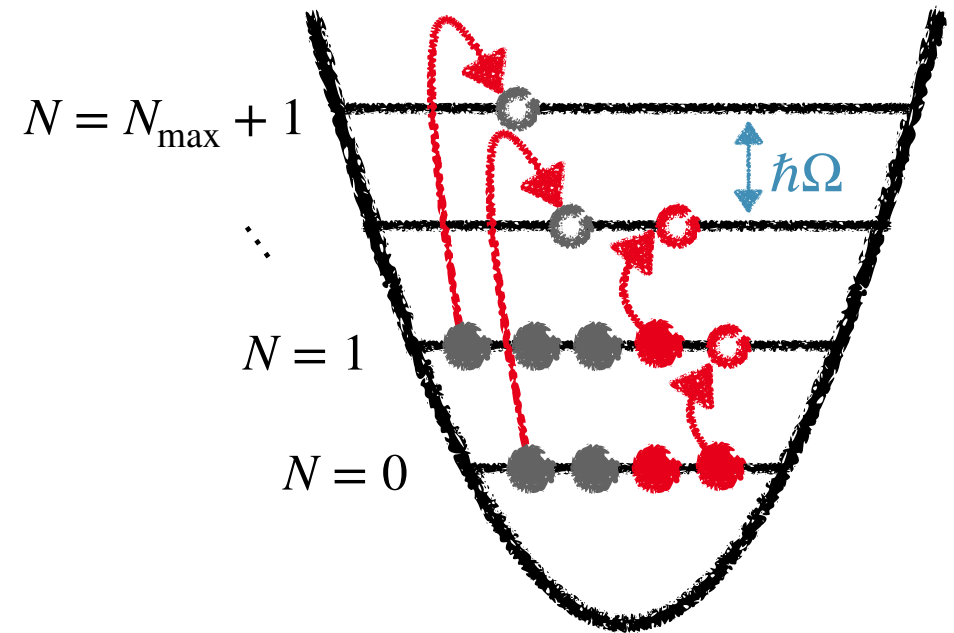
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- Two- (NN) and three-body (3N) forces from χ EFT:

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



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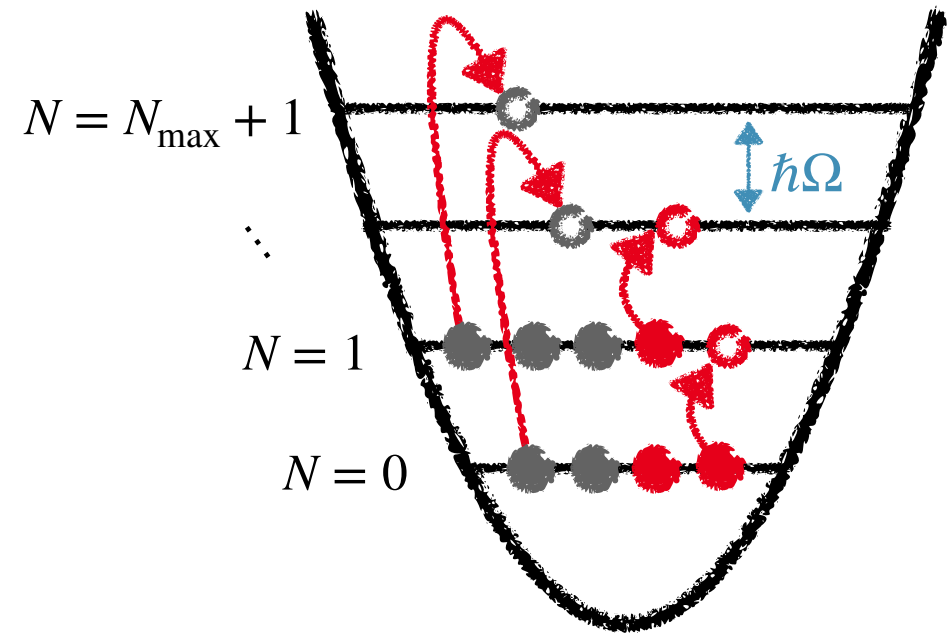
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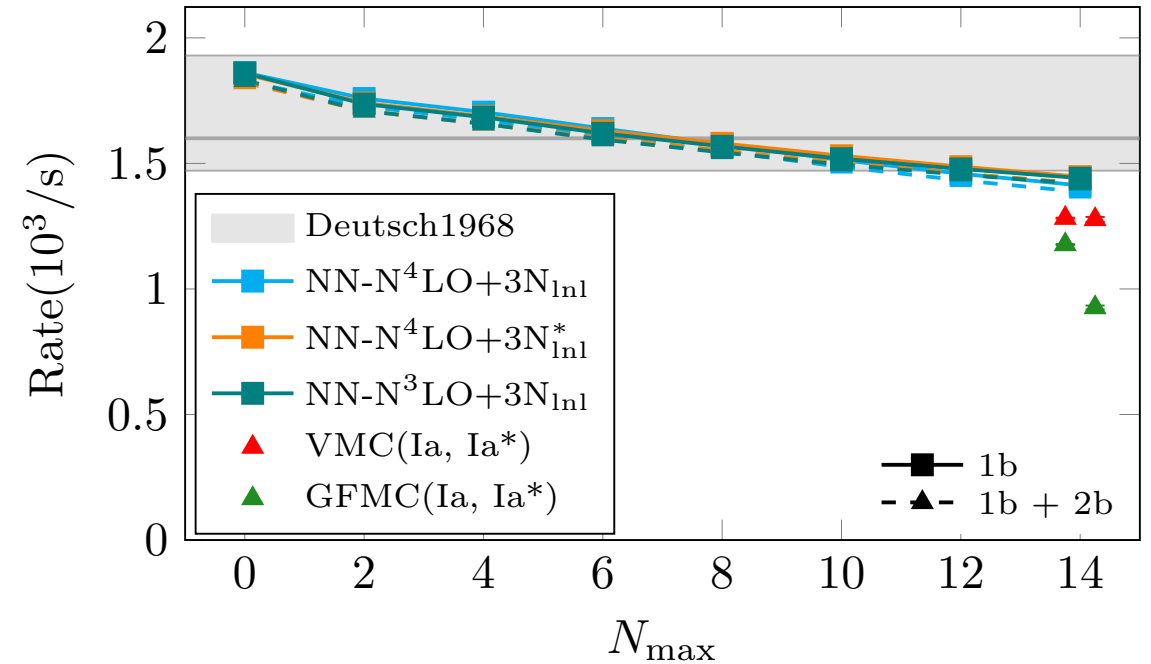
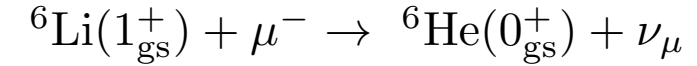
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- Expansion in Harmonic Oscillator (HO) basis:

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



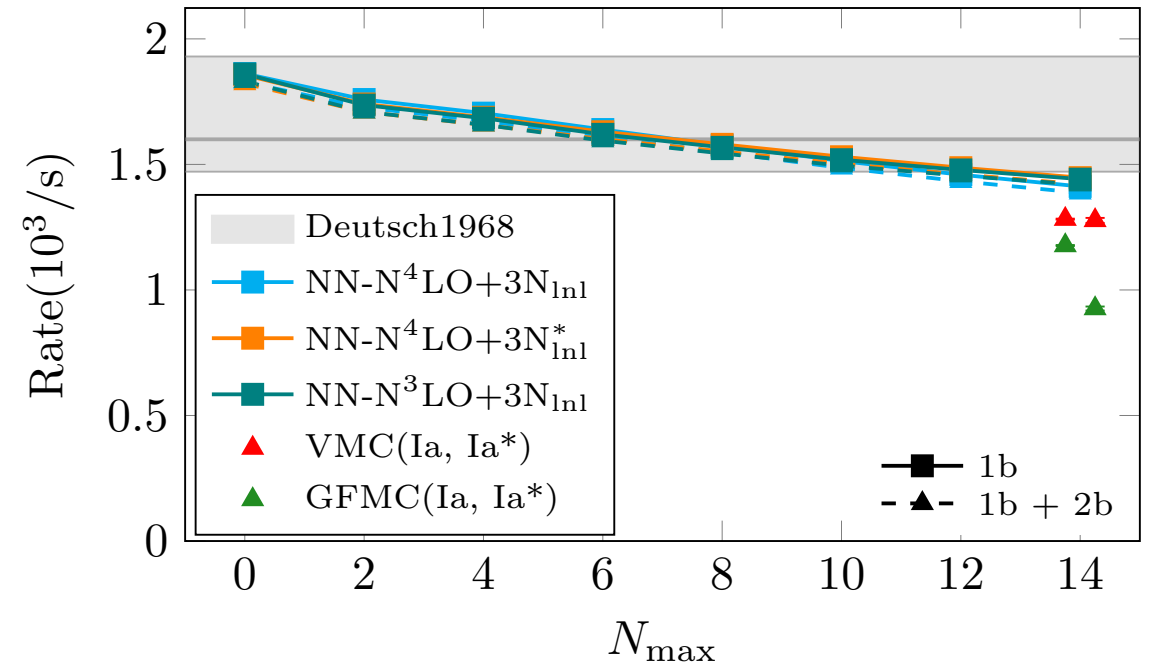
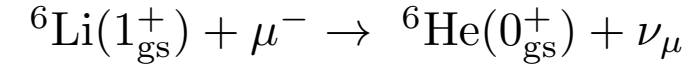
MUON CAPTURE TO THE GROUND STATE OF ${}^6\text{He}$



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

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- Calculations slightly underestimate the experiment



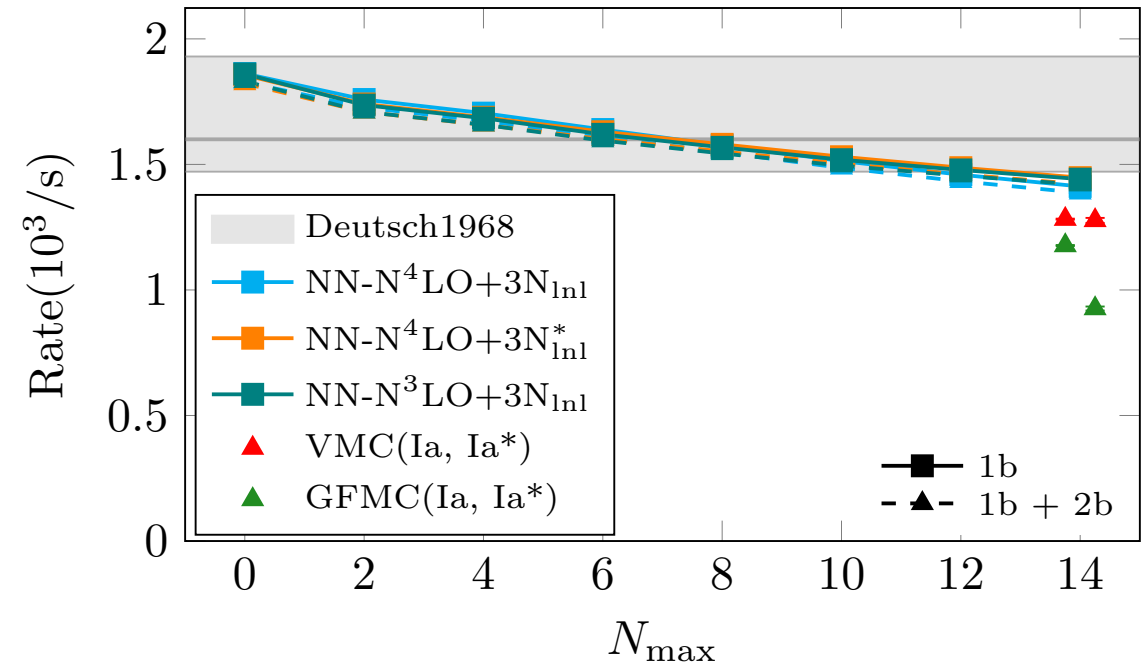
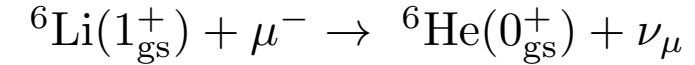
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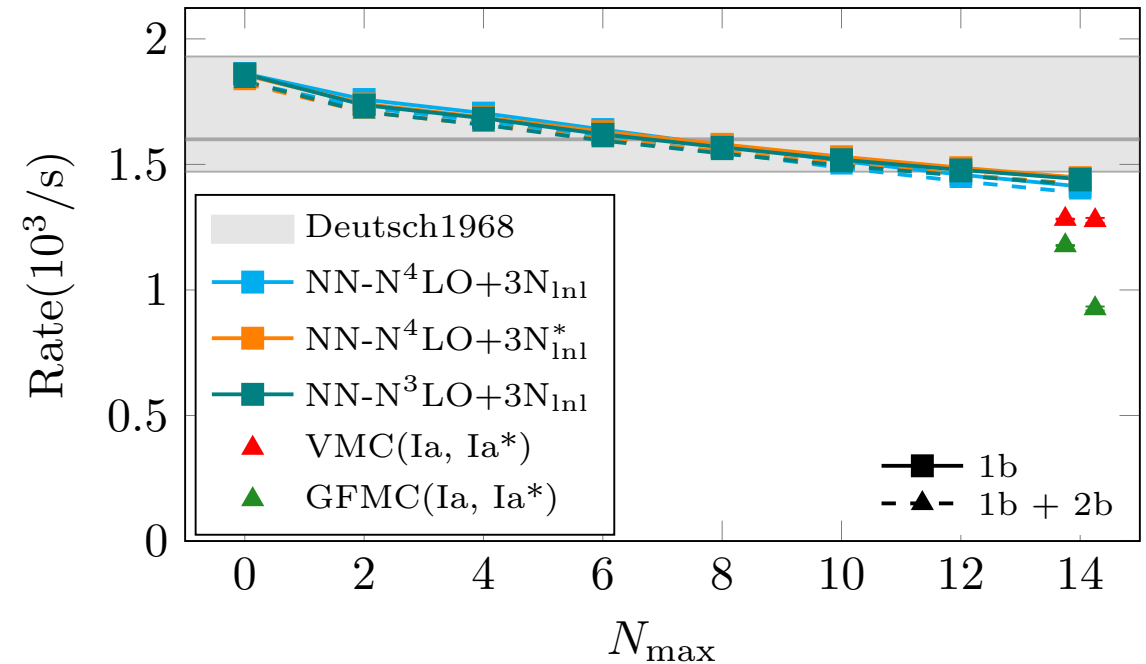
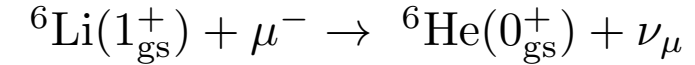
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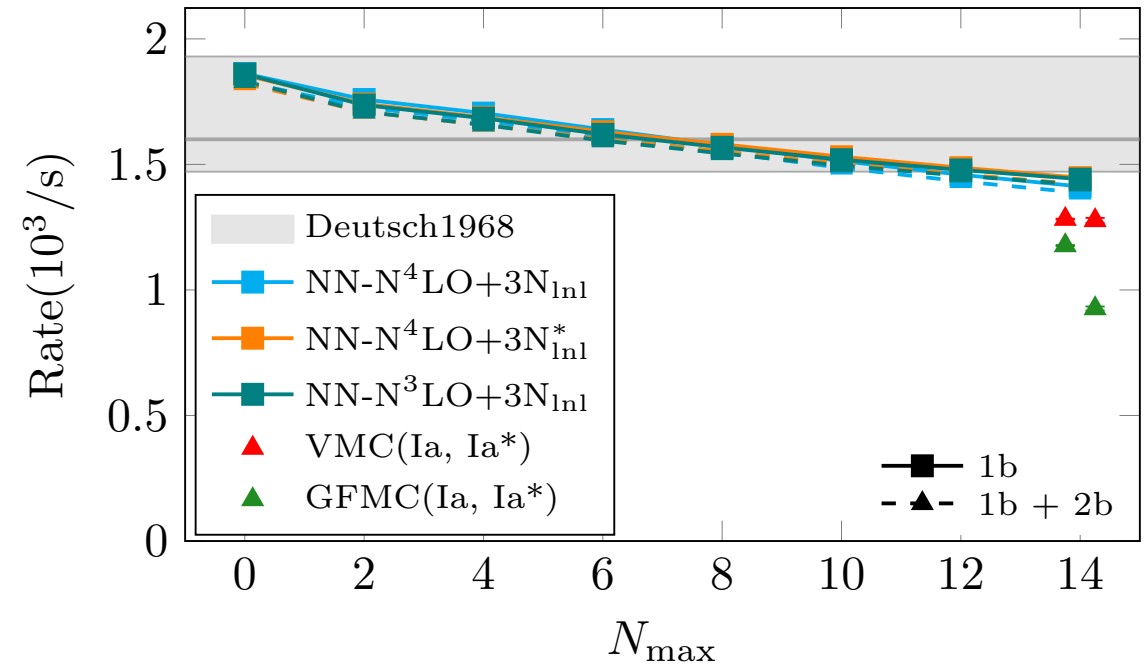
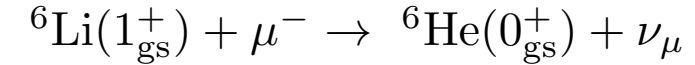
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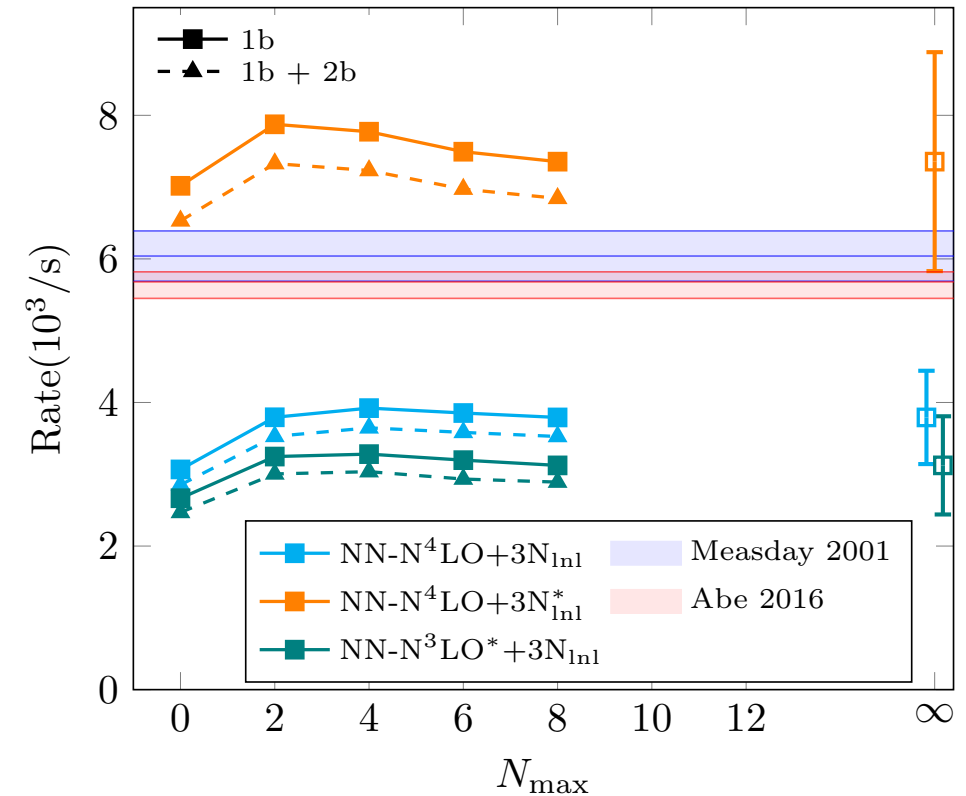
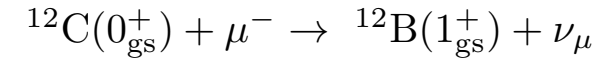
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LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C 109, 065501 (2024)



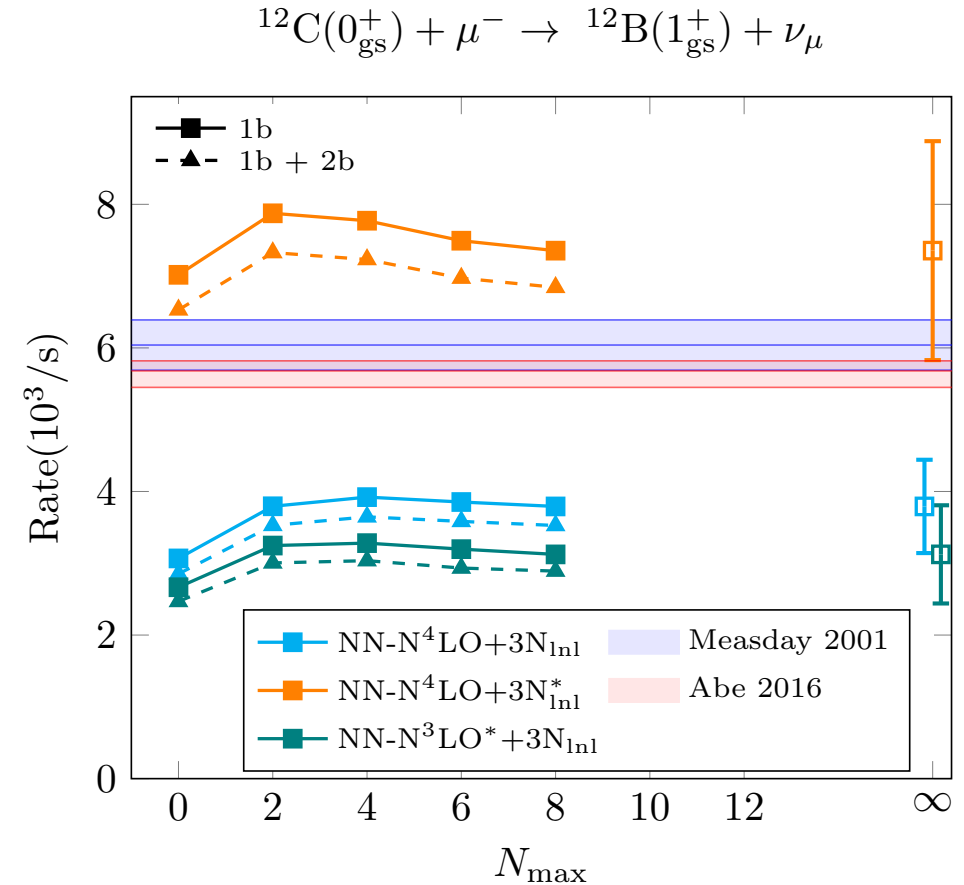
MUON CAPTURE TO THE **GROUND-STATE** OF ^{12}B



*LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C
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MUON CAPTURE TO THE **GROUND-STATE** OF ^{12}B

- Significant interaction dependence



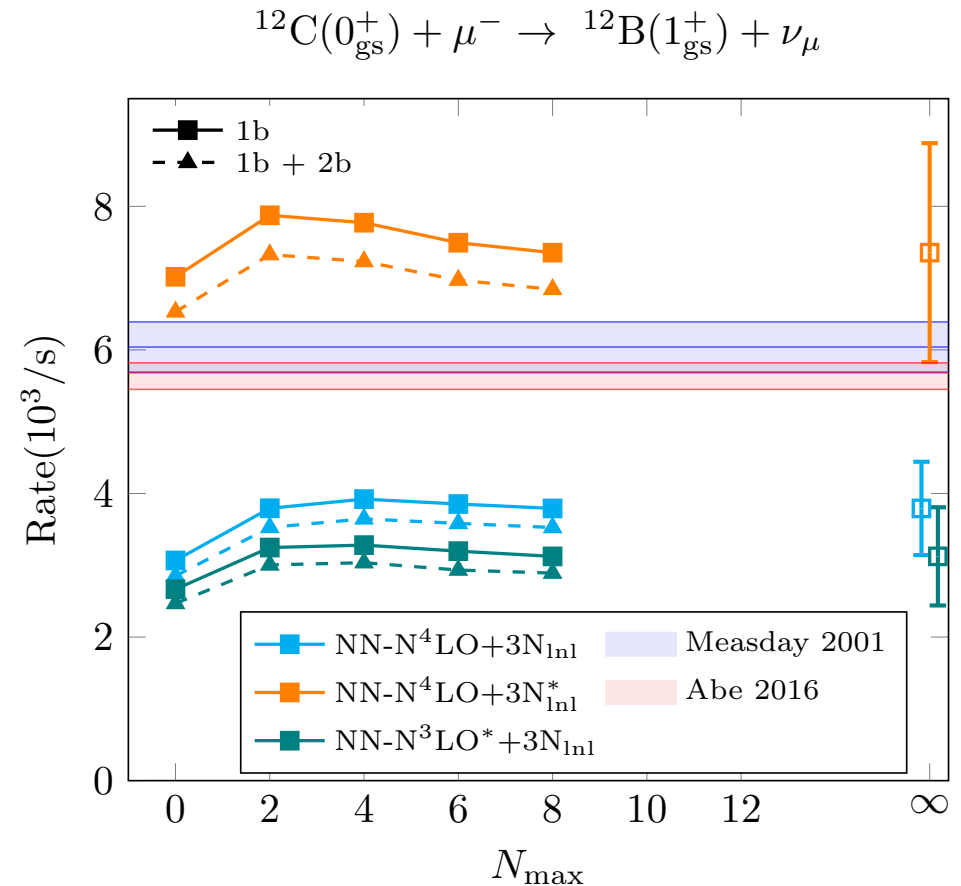
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- Significant **interaction dependence**

- The $\text{NN} - \text{N}^4\text{LO} + 3\text{N}_{\text{Inl}}^*$ interaction with the **subleading 3N term (E7)** most consistent with experiments

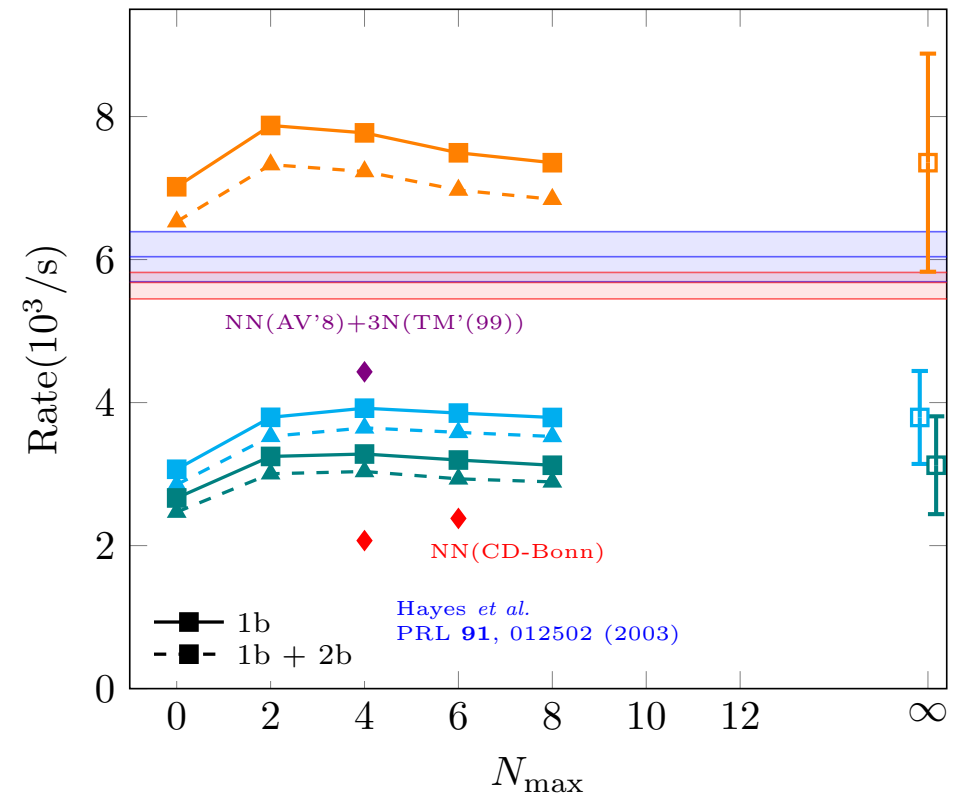
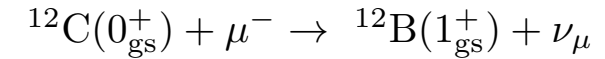
Girlanda, Kievsky, Viviani, Phys. Rev. C 84, 014001 (2011)



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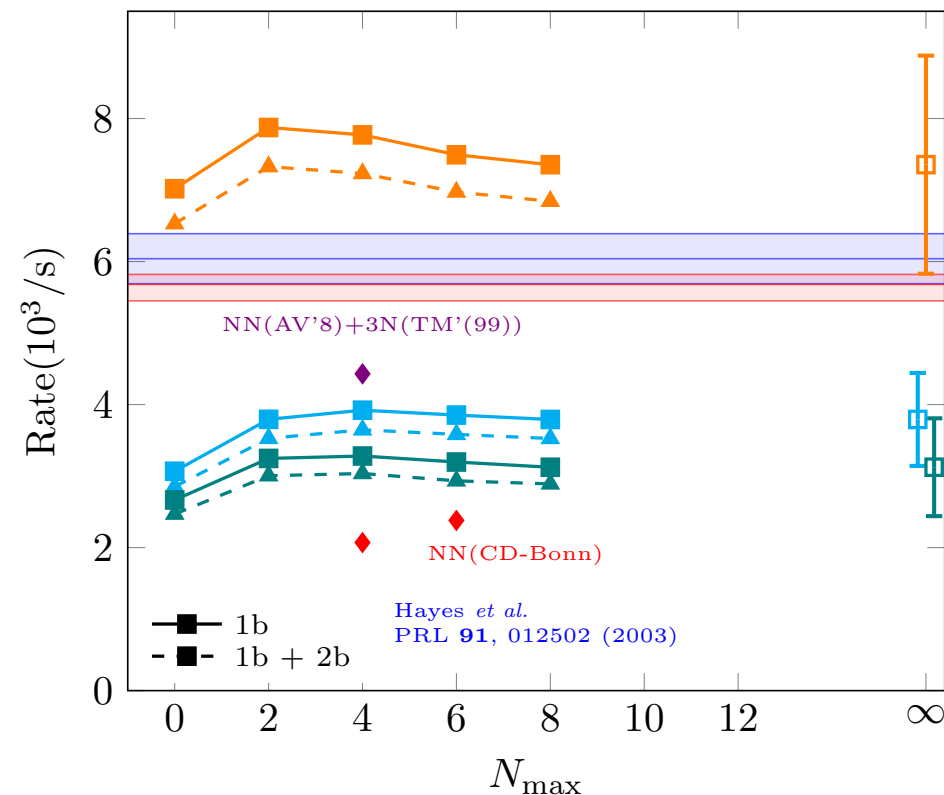
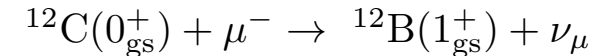
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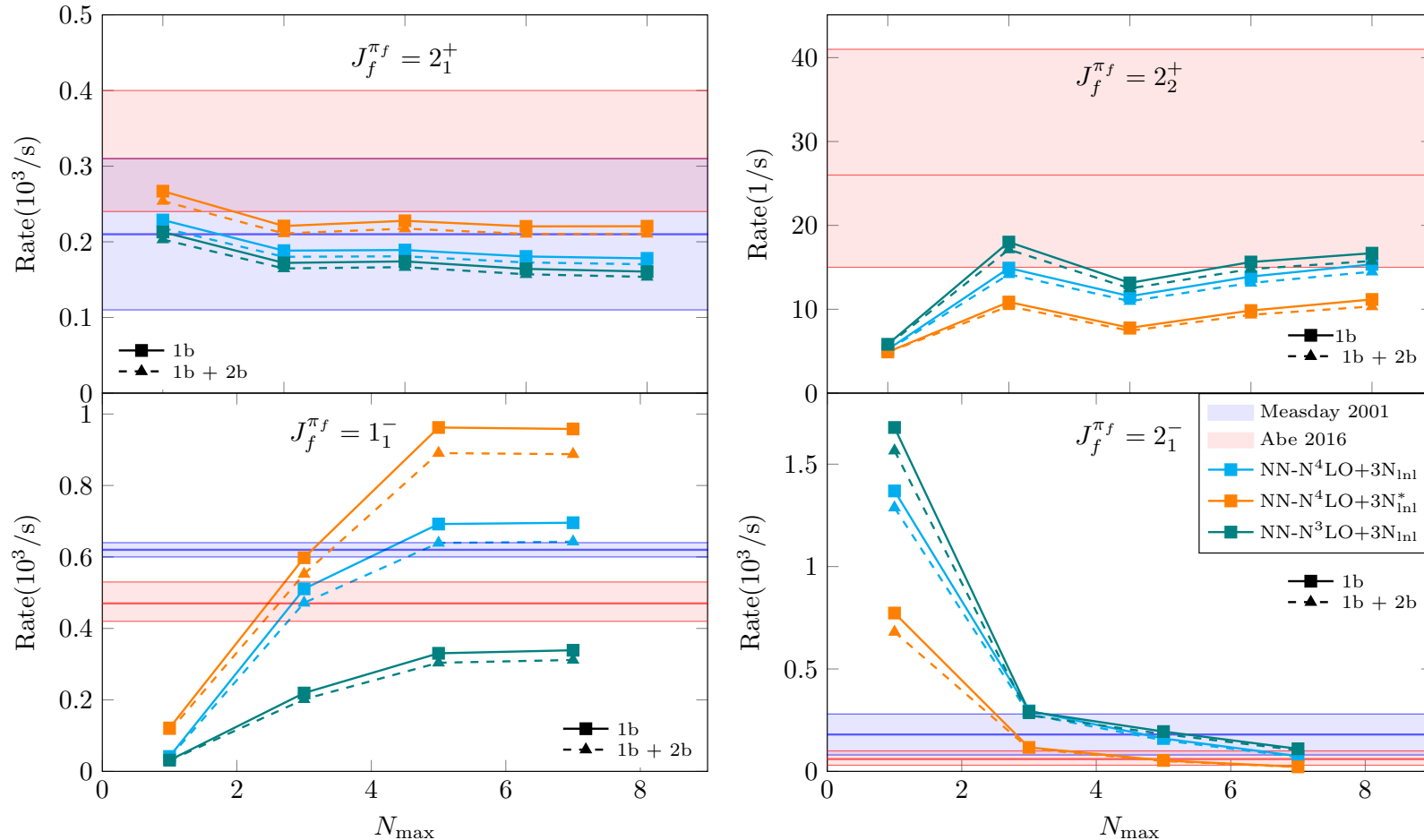
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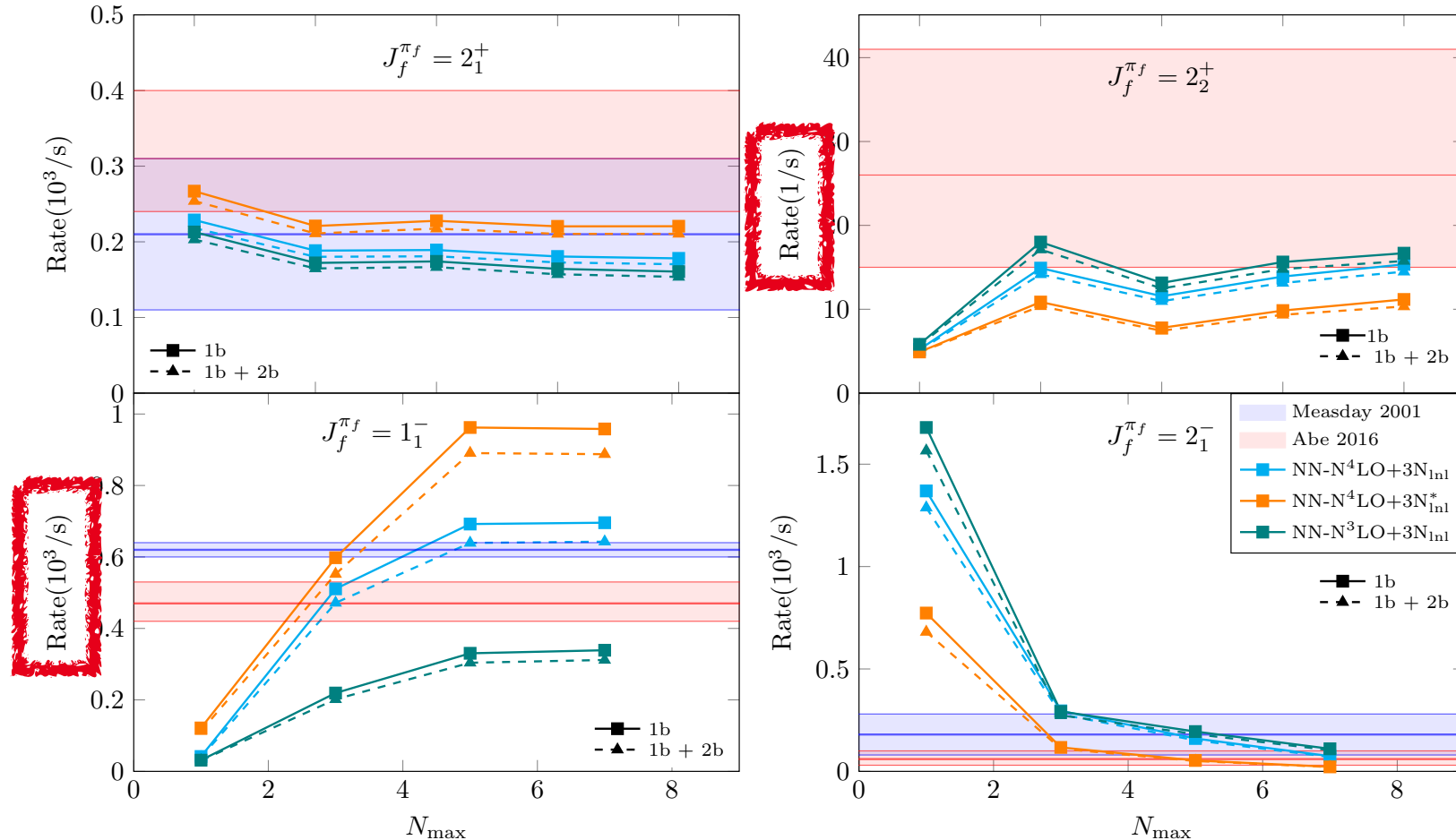
LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C 109, 065501 (2024)

MUON CAPTURE TO THE EXCITED STATES OF ^{12}B



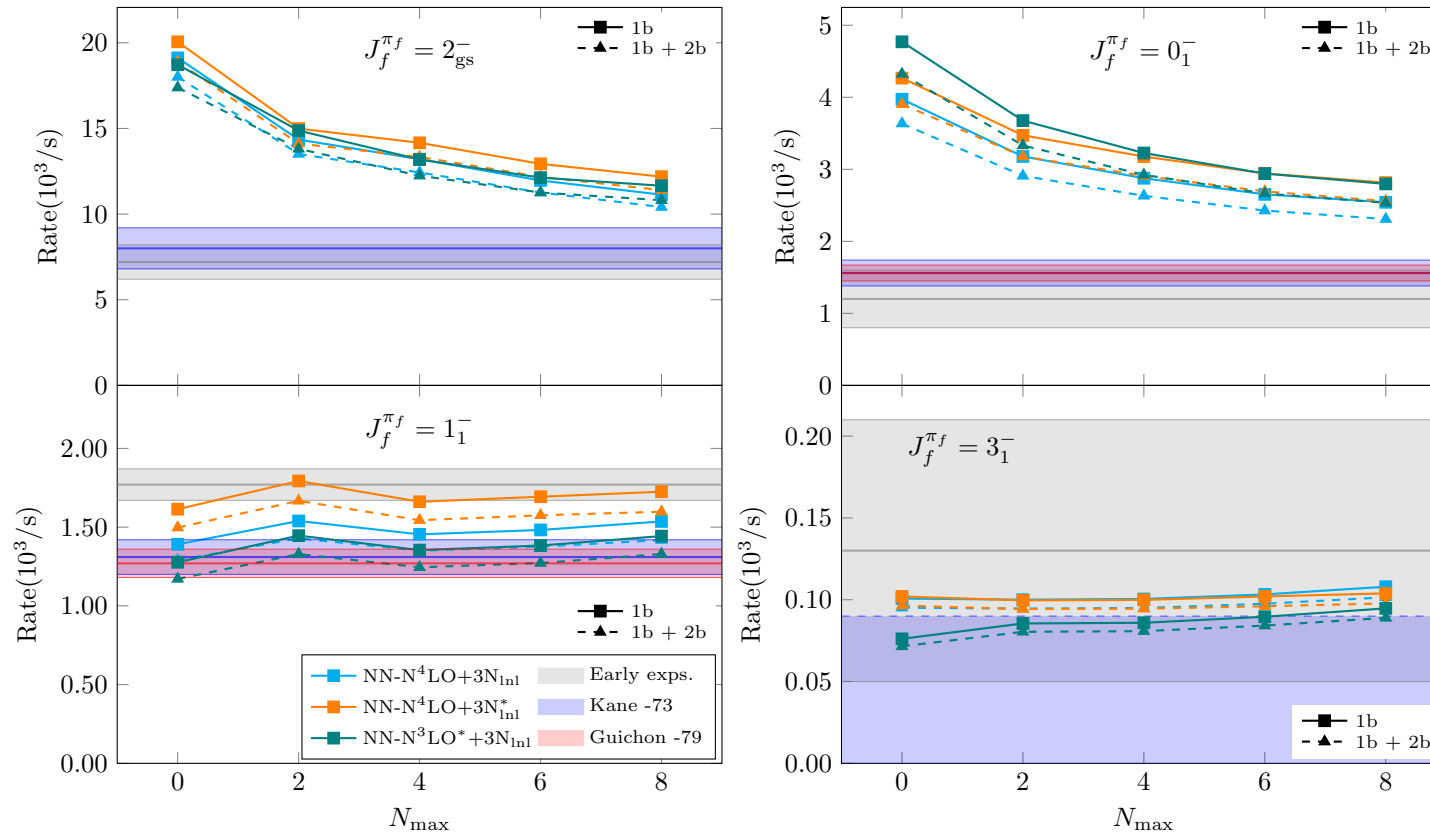
LJ, P. Navrátil, J. Kotila, K. Kravvaris, *Phys. Rev. C* 109, 065501 (2024)

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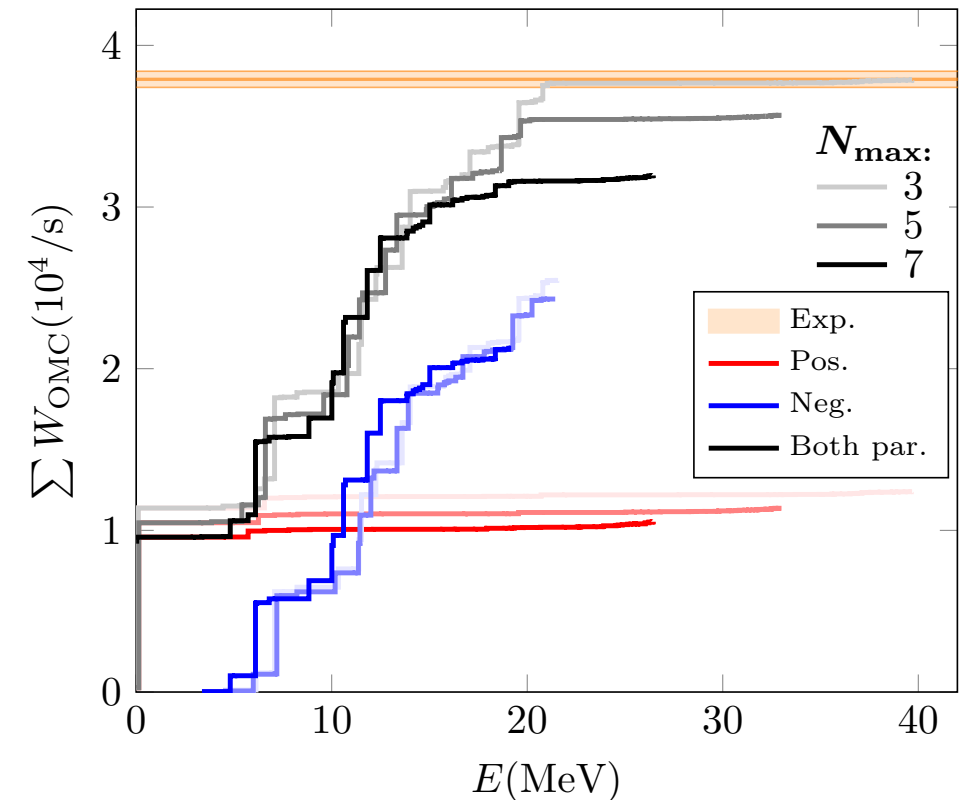
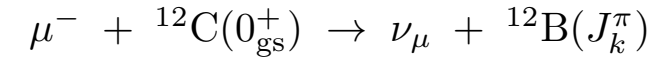
MUON CAPTURE TO ^{16}N



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

TOTAL MUON CAPTURE RATES

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

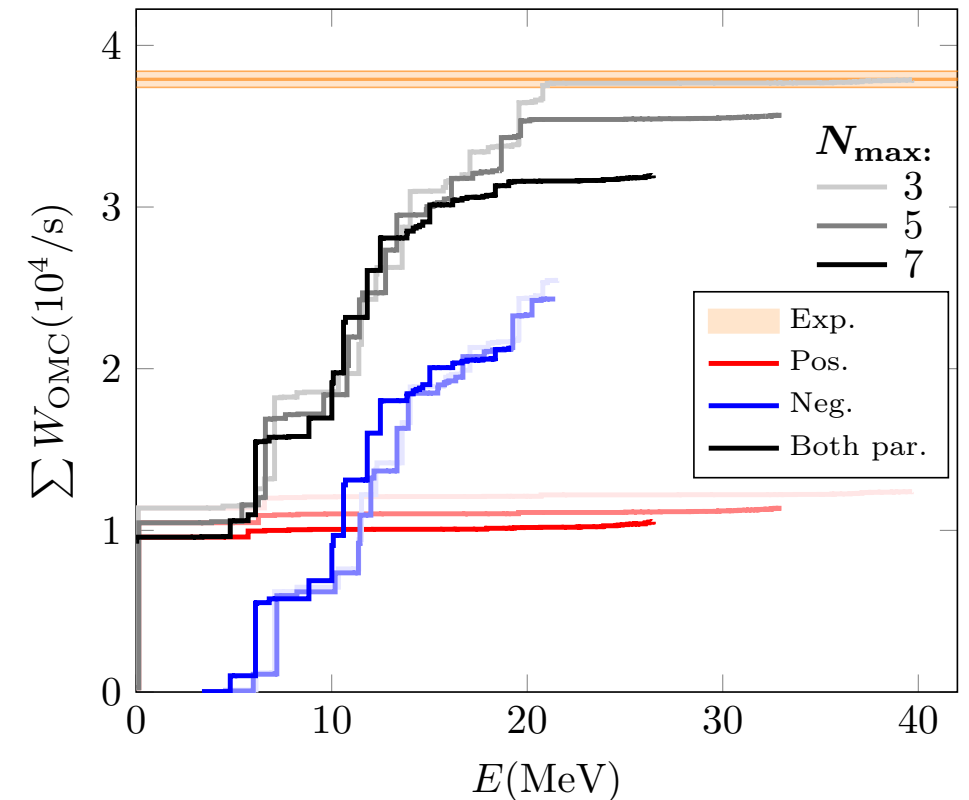
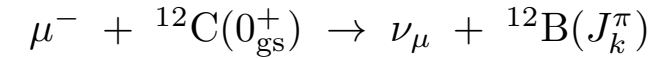


*LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C
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TOTAL MUON CAPTURE RATES

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- Rates obtained by summing over **~50 final states of each parity**

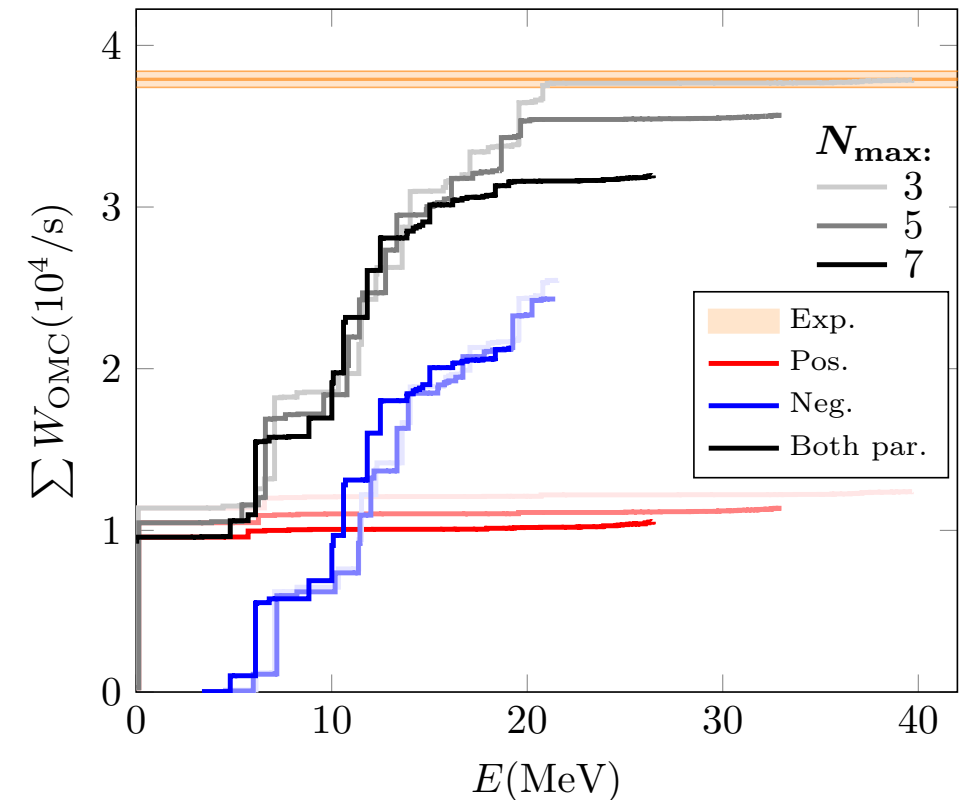
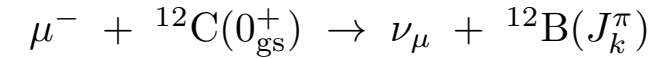


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- Summing up the rates up to ~20 MeV, we capture **~85% of the total rate** in both ^{12}C and ^{16}N

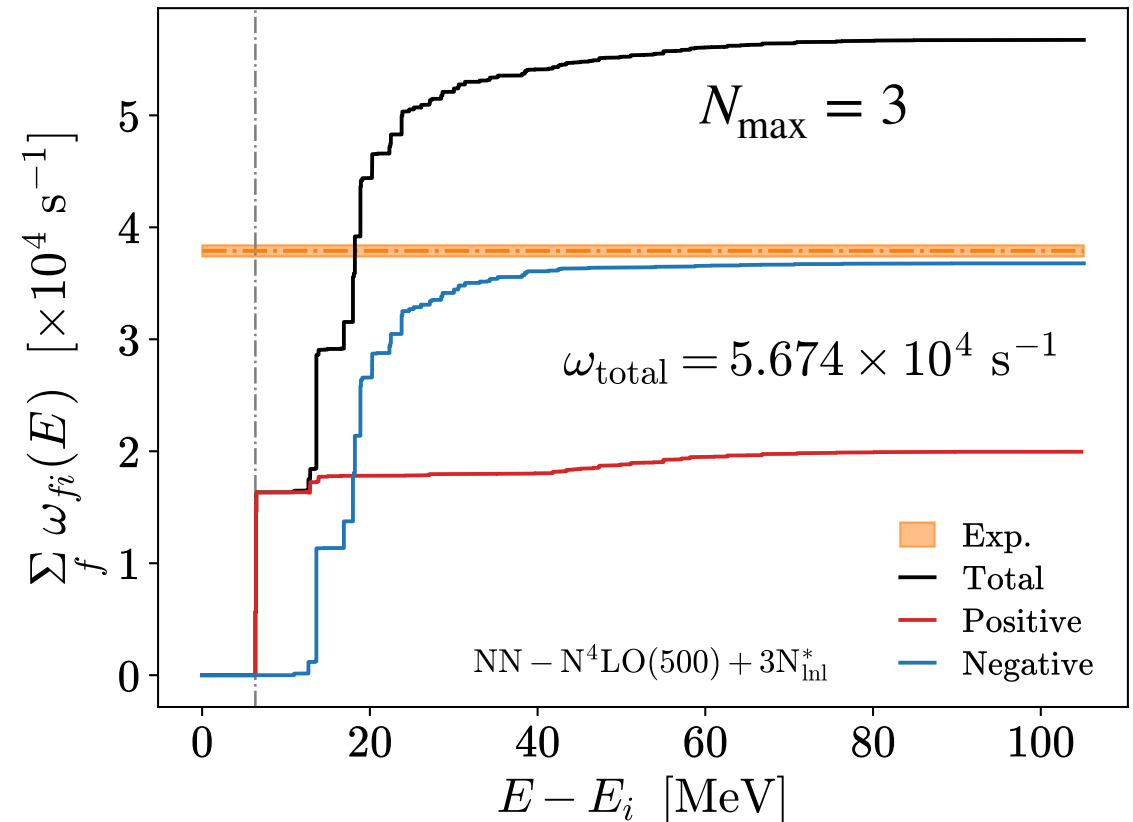


LJ, P. Navrátil, J. Kotila, K. Kravvaris, *Phys. Rev. C*
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TOTAL MUON CAPTURE RATES

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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
- **Better estimation of the total rates using the Lanczos strength function method underway**

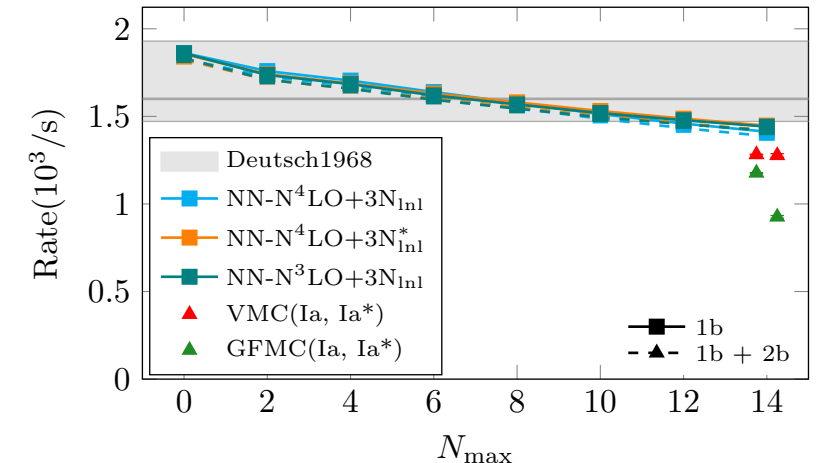
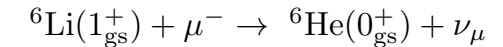
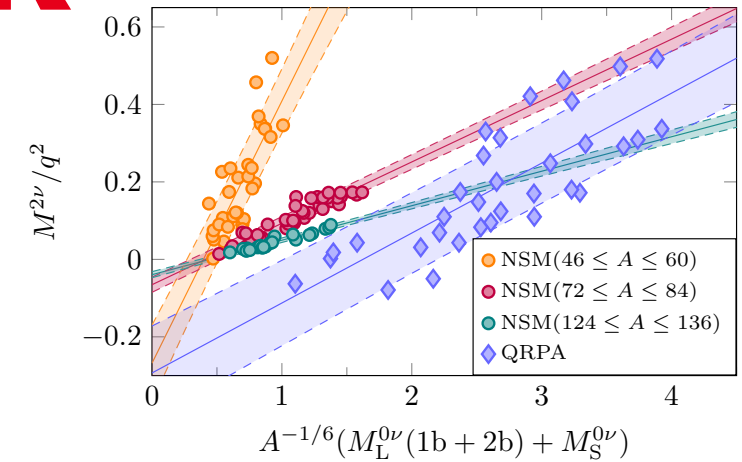


*D. Araujo Najera, M. Gennari, LJ, M. Drissi,
P. Navrátil, work in progress*

SUMMARY AND OUTLOOK

- We found correlations between the nuclear matrix elements of $0\nu\beta\beta$ decay and DGT reactions and $2\nu\beta\beta$ decay
- Ordinary muon capture on light nuclei is well described by *ab initio* nuclear theory

- Consistent study of the χ EFT corrections to $0\nu\beta\beta$ decay in an *ab initio* framework
- Extend the *ab initio* studies on muon capture in heavier nuclei including exact two-body currents





THANK YOU TO COLLABORATORS



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